USE OF SPATIAL TRANSFORMATIONS AND REFERENCE FRAMES:

INDIVIDUAL DIFFERENCES IN SPATIAL ABILITY

by

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ABSTRACT

The use of spatial transformations is ubiquitous in everyday cognitive processing from reading maps to planning actions to reasoning. Use and proficiency in spatial transformations may vary based on both spatial ability and spatial expertise. Spatial ability is the ability to create, maintain, and transform visual imagery. Spatial expertise is knowledge, skills, or characteristics related to spatial thinking that can be used to differentiate outstanding individuals from less outstanding individuals. Three classes of spatial transformations—object-based (i.e., object rotation), perspective-based (i.e., body rotation), and effector-based (i.e., body-part rotation)—and their relationship to three spatial abilities—spatial orientation, spatial visualization, and kinesthetic imagery—were examined. Participants (controls and dancers) completed psychometric tests predicted to recruit the three spatial ability factors. They also performed timed computer-based spatial transformations of bodies and body-parts in two types of tasks (same/different and left/right). Overall, performance on the transformations as a function of task type and stimulus was predicted differentially by the three spatial ability factors. This suggests that three distinct processes are involved. Furthermore, dancer performance on the transformation tasks suggested more dynamic versus static processing of stimuli than controls.

For Eric, who has been remarkably patient

and unwavering in his love and support

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GENERAL INTRODUCTION

The ability to transform visuospatial images is important for everyday activities, such as navigation, rearranging furniture, and tool use. For example, when giving driving directions, one must engage in spatial perspective taking, giving turn-by-turn instructions that correspond to the driver's spatial orientation. This involves rotating a mental map so that it corresponds to the appropriate orientation. According to the multiple systems framework, transformations of visuospatial images rely on representations in different spatial frames of reference (Zacks & Michelon, 2005), which include three distinct classes of transformations: object-based (i.e., object rotation), perspective-based (i.e., body rotation), and effector-based (i.e., body-part rotation) transformations. Presumably, these different transformation processes involve different types of spatial ability as evidenced by the variation in performance found across individuals in reading maps, solving geometry problems, or playing video games (Hegarty & Waller, 2005). The existing literature on individual differences has noticeably focused on whole body and object-based transformations but not effector-based transformations (e.g., Hegarty & Waller, 2004; Jola & Mast, 2005). Effector-based transformations are crucial in motor simulation (i.e., imagining and performing body movements). Motor simulation is essential to understanding, learning, and generating actions. My goal is to understand how different spatial transformations may recruit different processes and how this may be influenced by spatial ability and/or spatial expertise.

The first aim of this thesis is to test the relationship among different types of spatial transformations and spatial ability. *Spatial ability* is the ability to create, maintain, and transform visual imagery (Lohman, 1979). Three spatial ability factors of particular interest are spatial orientation, which is the ability to mentally transform one's perspective relative to spatial forms, spatial visualization, which is the ability to mentally transform objects, and kinesthetic imagery, which is the ability to simulate or mentally rehearse motor movement. While existing behavioral and neuroimaging data support a dissociation between object-based and perspective-based transformations (e.g., Hegarty & Waller, 2004; Zacks, Hazeltine, Tversky, & Gabrieli, 1999; Zacks & Michelon, 2005; Zacks, Rypma, Gabrieli, Tversky, & Glover, 1999), the mechanisms involved in effector-based transformations are less clear. Effector-based transformations are often grouped with perspective-based transformations under the broader heading of egocentric transformations (Creem-Regehr, Neil, & Yeh, 2007; Zacks & Michelon, 2005). Neuroimaging studies suggest that effector-based transformations involve kinesthetic representations rather than visual representations implying that effector-based transformations may involve separate mechanisms from object-based and perspective-based transformations (Creem-Regehr, et al., 2007; Kosslyn, Digirolamo, Thompson, & Alpert, 1998; Parsons, et al., 1995; Vingerhoets, De Lange, Vandemaele, Deblaere, & Achten, 2002; Zacks & Michelon, 2005). However, these kinesthetic representations interact with visuospatial representations used during spatial reasoning particularly for object-based transformations and could utilize similar mechanisms to object-based transformations (e.g., Sekiyama, 1982; Zacks, 2008). Additionally, studies suggest that the kinesthetic representations involved in mental rotation utilize motor simulation and motor imagery (e.g. Jeannerod & Frak, 1999; Kosslyn, et al., 1998). To date, all three types of spatial transformations have not been compared in the same study. Participants will complete psychometric tests of the three spatial ability factors as well as perform desktop computer-based spatial transformation tasks that measure reaction time and accuracy. A confirmatory factor analysis (CFA) will be performed on the psychometric test scores to confirm that the test scores are representative of three distinct factors. The factor scores from the CFA will then be used to test for different mechanisms underlying the spatial transformation tasks. Specifically, it is hypothesized that greater spatial ability for the factors of spatial orientation, spatial visualization, and kinesthetic imagery predicts perspective-, object-, and effector-based transformation ability, respectively.

The second aim of this thesis is to use spatial expertise to further test the relationship among the three types of spatial transformations. Spatial experts can be defined both by their spatial abilities and by their training. *Spatial expertise* is defined as knowledge, skills, or characteristics related to spatial thinking that can be used to differentiate outstanding individuals from less outstanding individuals. Scientific research has customarily studied neuropsychological cases or dysfunction in order to gain a better understanding of functional significance. A more novel approach is to highlight superior function, which may provide better insight into how to improve in these spatial domains that are so critical to our everyday functioning (Ericsson, Krampe, & Tesch-Römer, 1993; Obler & Fein, 1988). Specifically, it is hypothesized that experts with greater experience utilizing specific spatial frames of reference will show an advantage for tasks that require the spatial transformation related to their expertise. It is also predicted that processing may differ in systematic ways for spatial experts. In the existing literature, investigations of the contribution of spatial expertise to the processing of spatial transformations have been inconclusive. Expert performance could be at the extremes of normal performance (Aim 1) or experts could be utilizing different processes to solve these tasks. Experts (i.e., dancers) and controls will be compared on psychometric tests of the three spatial ability factors to see if experts differ from novices on specific factors of spatial ability. Behavioral differences on computer-based reaction time spatial transformation tasks will also be evaluated as a function of expertise group.

Factor-analytic Approach to Visuospatial Abilities

The existing literature supports the observation that spatial ability is multidimensional (e.g., Carroll, 1993; Hegarty & Waller, 2005; Lohman, 1979; Poltrock & Brown, 1984). This particular view of the nature of spatial ability is referred to as the factor-analytic approach to visuospatial abilities and is commonly used to explain and organize spatial test performance. Historically, factor analysis was the principal approach in the study of spatial abilities by early researchers. Factor analysis research set out to formulate new measures of spatial ability, to determine if spatial ability was made up of different factors, and to establish spatial ability as a separate construct from general intelligence.

The factor-analytic approach to visuospatial abilities has identified the basic dimensions of spatial thinking that traditional tests of spatial ability are assumed to measure (Carroll, 1993; Hegarty & Waller, 2005). These previous studies have identified different factors of visuospatial ability including spatial relations and orientation (i.e., mental transformation of one’s perspective relative to spatial forms), perceptual speed (i.e., the speed at which simple tasks involving visual perception are carried out), closure speed (i.e., the speed at which one can access representations in long term memory), kinesthetic imagery (i.e., simulating or mentally rehearsing motor movement), visualization (i.e., mental transformation of objects), and visual memory (Carroll, 1993; Lohman, 1988; McGee, 1979a; Michael, Guilford, Fruchter, & Zimmerman, 1957).

Existing research has also identified the associated perceptual and cognitive processes tapped by these factors (e.g., Hegarty & Waller, 2005; Just & Carpenter, 1985; Lohman, 1988; Pellegrino & Kail, 1982). The processing demands of spatial ability tests include encoding a visual stimulus, forming a visual representation, maintaining a representation in working memory, transforming a representation, evaluating a visual stimulus against a representation in working memory, and giving a response. Individual differences in spatial ability may be rooted in differences in processing. For example, speed of processing and strategy use may differentially affect performance. Mumaw, Pellegrino, Kail and Carter (1984) studied individual differences in performance on a speeded mental rotation task. In a timed setting, participants were asked to make judgments about whether two-dimensional rotated and mirrored stimulus images were matched or mismatched with a reference image. Individual differences in spatial ability in performing this task were associated with speed rather than accuracy, where high spatial ability individuals were able to complete more problems at a high level of accuracy. The authors conclude that high spatial ability individuals were faster than low spatial ability individuals in encoding and evaluating the stimuli. In a study by Just and Carpenter (1985), participants performed a Cube Comparisons test (Thurstone, 1938). In the Cube Comparisons test, the participant is presented with two cubes that have a letter or number on each face. Only three faces of each cube are visible and the participant is asked to make a judgment about whether or not the two images could depict the same cube or if they were different cubes. Just and Carpenter identified four different strategies that could be used in this mental rotation task – a mental rotation strategy around standard axes (i.e., x, y, or z axis), a mental rotation strategy around task-defined axes (i.e., an arbitrary axis that is the most appropriate and efficient for the task), a strategy comparing orientation-free descriptions (i.e., using the relative relationships between the letters or numbers without regard to orientation of the cubes), and a perspective change strategy (i.e., imaging one's position as changing relative to a cube whose position remains constant). After making a same or different response, participants were then asked to verbally report the strategy they used for that trial. Most participants reported using a mental rotation strategy to complete the task. Interestingly, low and high spatial ability participants used different mental rotation strategies. Low spatial ability participants used a mental rotation strategy around standard axes while high spatial ability participants used a mental rotation strategy around task-defined axes. This difference in strategy use accounted for greater speed and flexibility in the high spatial ability individuals compared to the low spatial ability individuals.

While spatial ability as associated factors and processes is widely accepted, characterization of those factors and processes remains a contentious issue. In a review of research using a factor-analytic approach to visuospatial ability, Hegarty and Waller (2005) highlight conflicts in the literature. Paper-and-pencil tests are normally used to assess spatial ability (Ekstrom, French, Harman, & Dermen, 1976; Silverman & Eals, 1992). However, throughout the literature the same tests have been used to assess different factors. For example, Carroll (1993) cited the Cube Comparisons test and the

Guilford-Zimmerman test of Spatial Orientation among others as tests of spatial visualization while Michael, Guilford, Fruchter, and Zimmerman (1957) cited those same tests as a measure of spatial relations and orientation. As a consequence of the lack of consensus in how visuospatial ability factors have been characterized and differentiated, the question still remains as to how many discrete factors comprise spatial ability and how are they defined.

Spatial Transformations

There is some evidence to suggest that the factor-analytic approach to spatial ability may map onto transformations of spatial frames of reference (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001; Zacks, Mires, Tversky, & Hazeltine, 2002). The factor-analytic approach to visuospatial ability alludes to a relationship between different aspects of spatial ability and spatial frames of reference. For instance, Thurstone (1950) defined spatial relations and orientation as a visuospatial factor that involves the ability to understand spatial relations relative to one's body frame of reference, that is, relative to an egocentric reference frame. Michael, et al. (1957) identified the visuospatial factor of spatial visualization as involving the "mental manipulation" of objects without reference to self, that is, relative to an allocentric reference frame.

Three spatial ability factors of interest related to the use of reference frames and to this thesis are emerging in the literature – spatial orientation (SO), spatial visualization (SV), and kinesthetic imagery (KI). Researchers have previously indicated that these are separable abilities (Guilford & Zimmerman, 1948; McGee, 1979a; Thurstone, 1950). Spatial orientation, for our purposes, will refer to the mental transformation of one's perspective relative to spatial forms. Spatial visualization will refer to the mental transformation of objects. Kinesthetic imagery will refer to ability to simulate or mentally rehearse motor movement. These definitions are consistent with other researchers (Coleman & Gotch, 1998; Friedman, 1995; Lawton, 1994; Michael, et al., 1957). For example, Michael, Guilford, Fruchter, and Zimmerman (1957) proposed three spatial ability factors – spatial relations and orientation, visualization, and kinesthetic imagery. The authors defined spatial relations and orientation as the ability to understand the spatial configuration of objects with respect to the observer's body as the frame of reference. Visualization was defined as the manipulation of objects involving a specified sequence of transformations. Kinesthetic imagery was defined as a left/right discrimination with respect to the human body given imagined movement in response to a visual stimulus.

Recent behavioral evidence supports the idea that spatial orientation and spatial visualization are distinct spatial abilities. Paper-and-pencil tests of spatial relations and orientation, and spatial visualization rely on different types of mental transformations – egocentric perspective transformations and object-based or allocentric spatial transformations (Zacks, Mires, et al., 2002), respectively. These two types of transformations inherently involve the use of different reference frames. In these studies, egocentric perspective transformations are associated with spatial orientation and object-based spatial transformations are associated with spatial visualization (Hegarty & Waller, 2004; Jola & Mast, 2005; Kozhevnikov, Blazhenkova, & Becker, 2010; Kozhevnikov & Hegarty, 2001; Kozhevnikov, Kosslyn, & Shephard, 2005; Zacks, Mires, et al., 2002). Kozhevnikov and Hegarty (2001) utilized a confirmatory factor analysis to show that spatial orientation and spatial visualization are separable but highly correlated spatial abilities. Kozhevnikov and Hegarty used perspective-taking tests (Object Perspective, Map Perspective, and Santa Barbara Sense of Direction) and mental rotation tasks (Cube Comparison, Card Rotation, Paper Folding, and Guilford-Zimmerman Test) to tap into these two abilities. A distinction between spatial orientation and spatial visualization was made based on the representational system used. Spatial orientation was defined as the ability to understand object locations relative to the observer's body and to imagine taking a different spatial perspective using a self-to-object representational system. Spatial visualization, or object manipulation, was defined as the ability to understand spatial relations and to mentally transform objects from a stationary viewpoint using an object-to-object representational system. Hegarty and Waller (2004) offered further support for this notion demonstrating a dissociation between these two highly correlated factors. Hegarty and Waller evaluated performance on perspective-taking tests (Revised version of the Object Perspective, Money Standardized Test of Direction Sense, and Pictures test) that are primarily solved by an egocentric spatial transformation strategy and mental rotation tasks (Vandenberg Mental Rotation, Flags, and Card Rotation) that are primarily solved by an object-based transformation strategy using a confirmatory factor analysis. The hypothesis that perspective-taking and mental rotation are separable factors was tested by seeing whether a one- or two-factor model better fit the data. Hegarty and Waller did concede that although mental rotation and perspective-taking rely on different types of spatial transformations, they may rely on common processes. Zacks, Mires, Tversky and Hazeltine (2002) used a clever experiment design to establish egocentric perspective transformations and object-based spatial transformations as discrete processes. Zacks, et al. argue that egocentric perspective transformations and object-based spatial transformations have unique chronometric profiles, that is, response times in tasks tapping each type of mental transformation differ as a function of different processing systems. To test this hypothesis, the same stimuli, participants, and task parameters were employed. In addition to traditional psychometric tests of spatial ability (Vandenberg Mental Rotation, Map Reading test, and Perspective-taking test), participants were presented with 2D line drawings of human bodies with one of their arms outstretched. The stimuli were presented in varying orientations. In the egocentric perspective task (left/right task), participants judged whether in an image the person had their right or left hand outstretched. In the object-based spatial transformation task (same/different task), participants judged if a pair of images were identical or mirror-images. Different response time patterns were seen for the same/different task compared to the left/right task consistent with the authors' predictions and previous studies that support a dissociation. These studies are in line with findings in the experimental cognitive literature supporting a dissociation between tasks depending on egocentric perspective transformations and object-based spatial transformations (e.g., Huttenlocher & Presson, 1973; Huttenlocher & Presson, 1979; Simons & Wang, 1998; Wraga, Creem, & Proffitt, 1999).

According to the multiple systems framework, transformations of visuospatial images rely on representations in different spatial reference frames (Zacks, Mires, et al., 2002; Zacks, Ollinger, Sheridan, & Tversky, 2002; Zacks & Tversky, 2005). These representations can be characterized into three associated but distinct classes – object-centered, egocentric, and environmental reference frames. Transformations involve updating specific reference frames in relation to the other reference frames and can be defined as object-based, perspective, or effector-based transformations. Effector-based transformations refer to body part rotations. The multiple systems framework is compatible with previous definitions of perspective-, object-, and effector-based transformations (e.g., Callow & Roberts, 2010; Wraga, et al., 1999). In this framework, object-based transformations take place when an object-centered reference frame is updated relative to egocentric and environmental reference frames. For example, an object-based transformation occurs when a car moves down a street relative to a person (i.e., egocentric reference frame) waiting at a street corner (i.e., environmental reference frame). Perspective transformations take place when a person's eye-centered reference frame is updated relative to object-centered and environmental reference frames. In the example, a perspective transformation occurs when the person crosses the street while the car (i.e., object-centered reference frame) waits at the traffic light (i.e., environmental reference frame). Effector-based transformations are when a person's effector-centered reference frame is updated relative to object-centered and environmental references frames. An effector-based transformation occurs when the person pushes (i.e., hand-centered reference frame) the pedestrian crossing button (i.e., object-centered reference frame) on the traffic light post (i.e., environmental reference frame). Behavioral and neuroimaging research support the idea that each type of transformation utilizes some distinct processing resources and the efficiency by which these resources are used can differ by individual (e.g., Hegarty & Waller, 2005; Zacks, Hazeltine, et al., 1999; Zacks, Rypma, et al., 1999).

Spatial Expertise

The contribution of spatial expertise to the processing of spatial transformations has to date been explored in a limited way, with a focus on object-based transformations. Previous studies have demonstrated that while perspective transformations are typically easier for the general population than object-based transformations (Kozhevnikov & Hegarty, 2001), scientists such as chemists and physicists show superior performance on object-based transformations based on their experience with dynamic and static visualization of schematic images (Kozhevnikov, et al., 2010; Kozhevnikov, Motes, & Hegarty, 2007). On the other hand, in Steggemann, Engbert, and Weigelt (2011), motor experts showed greater response error for the object-based transformation task as compared to the perspective transformation task, but were worse in terms of accuracy on both tasks compared to controls. Jola and Mast (2005) tested dancers and nondancers on object mental rotation (MRT) and body mental rotation tasks (MBRT), but contrary to their hypothesis, they did not find a difference in performance between dancers and nondancers.

OVERVIEW OF THE PROJECT

The current individual differences literature on spatial thinking has primarily focused on perspective-based and object-based transformations but less is known about effector-based transformations (e.g., Hegarty & Waller, 2004; Jola & Mast, 2005). Based on the existing literature on effector-based transformations, it is unknown whether it is a distinct process from perspective- or object-based transformations or if it shares processes with either or both. In contrast to previous research, this thesis will test all three spatial transformations in one study utilizing the same participants, stimuli, and task parameters modeled after the experimental design from Zacks and colleagues (2002).

In order to understand if these different spatial transformations recruit different processes I will investigate how these processes may be moderated by spatial ability and/or spatial expertise. It is likely that processing differences or similarities for effector-based transformations are influenced by one's spatial orientation, spatial visualization, and/or kinesthetic imagery abilities. As stated above, this will be tested using a CFA to determine whether three different factors result from the psychometric tests, and second, by using the resulting factor scores to predict spatial transformation performance. Distinguishing the factors which predict spatial transformation performance will inform our understanding of the underlying processes involved in spatial transformations.

Spatial expertise as defined by spatial ability and training will be considered relative to individual differences in spatial ability and spatial transformation performance across the normal population (Chase & Simon, 1973; De Groot, 1978; Ericsson & Lehmann, 1996). To compare with the existing literature, formally trained dancers will be used to test my hypotheses. Dancers and nondancer controls will be compared on psychometric tests to see if dancers differ from controls in kinesthetic imagery ability based on their training and practice in codified dance and Laban's spatial awareness (Laban, 1950; Leman & Naveda, 2010). Behavioral differences on computer-based reaction time spatial transformation tasks will also be evaluated as a function of expertise group. If dancers are high in kinesthetic imagery ability then we would expect dancers to have an advantage on tasks and stimuli requiring kinesthetic imagery.

STUDY 1

Abstract

The use of spatial transformations is ubiquitous in everyday cognitive processing from reading maps to planning actions. Use and proficiency in spatial transformations may vary based on spatial ability. Spatial ability is the ability to create, maintain, and transform visual imagery. Three classes of transformations—object-based (i.e., object rotation), perspective-based (i.e., body rotation), and effector-based (i.e., body-part rotation)—and their relationship to three spatial abilities—spatial orientation, spatial visualization, and kinesthetic imagery—were examined. Participants (controls and dancers) completed psychometric tests predicted to recruit the three spatial ability factors. They also performed timed computer-based spatial transformations of bodies and body-parts in two types of tasks (same/different and left/right). Overall, performance on the transformations as a function of task type and stimulus was predicted differentially by the three spatial ability factors. This suggests that three distinct processes are involved.

Introduction

The ability to transform visuospatial images is important for everyday activities, such as navigation, rearranging furniture, and tool use. For example, when giving driving directions, one must engage in spatial perspective taking, giving turn-by-turn instructions that correspond to the driver's spatial orientation. This involves rotating a mental map so that it corresponds to the appropriate orientation. According to the multiple systems framework, transformations of visuospatial images rely on representations in different spatial frames of reference (Zacks & Michelon, 2005), which include three distinct classes of transformations: object-based (i.e., object rotation), perspective-based (i.e., body rotation), and effector-based (i.e., body-part rotation) transformations. Presumably, these different transformation processes involve different types of spatial ability as evidenced by the variation in performance found across individuals in reading maps, solving geometry problems, or playing video games (Hegarty & Waller, 2005). The existing literature on individual differences has noticeably focused on whole body and object-based transformations but not effector-based transformations (e.g., Hegarty & Waller, 2004; Jola & Mast, 2005). Effector-based transformations are crucial in motor simulation (i.e., imagining and performing body movements). Motor simulation is essential to understanding, learning, and generating actions.

The ability to perform spatial transformations may vary as a function of individual differences in spatial ability. It is known that there are differences in performance on spatial tasks as a function of spatial ability, such as superior performance in object mental rotation for high versus low spatial ability (e.g., Just & Carpenter, 1985). However, this relationship is lacking consideration of the multidimensional nature of spatial ability (e.g., Carroll, 1993; Hegarty & Waller, 2005; Lohman, 1979; Poltrock & Brown, 1984). This particular view of the nature of spatial ability is referred to as the factor-analytic approach to visuospatial abilities and is commonly used to explain and organize spatial test performance. Of particular interest are three spatial ability factors that may be related to the use of reference frames and spatial transformations – spatial orientation, spatial visualization, and kinesthetic imagery. Researchers have previously indicated that these are separable abilities (Guilford & Zimmerman, 1948; McGee, 1979a; Michael, et al., 1957; Thurstone, 1950). Spatial orientation, for our purposes, will refer to the mental transformation of one's perspective relative to spatial forms. Spatial visualization will refer to the mental transformation of objects. Kinesthetic imagery will refer to ability to simulate or mentally rehearse motor movement. These definitions are consistent with other researchers (Coleman & Gotch, 1998; Friedman, 1995; Lawton, 1994; Michael, et al., 1957). For example, Michael, Guilford, Fruchter, and Zimmerman (1957) proposed three spatial ability factors – spatial relations and orientation, visualization, and kinesthetic imagery. The authors defined spatial relations and orientation as the ability to understand the spatial configuration of objects with respect to the observer's body as the frame of reference. Visualization was defined as the manipulation of objects involving a specified sequence of transformations. Kinesthetic imagery was defined as a left/right discrimination with respect to the human body given imagined movement in response to a visual stimulus.

The influence of spatial ability factors has been examined with respect to differences in use of spatial frames of reference, but has been limited to perspective and object-based transformations. Investigations of spatial ability factors with respect to spatial transformations have typically focused on object-based tasks such as mental rotation (e.g., Lohman, 1986; McGee, 1979; Shepard & Metzler, 1971) using abstract blocks or whole bodies. Zacks, Mires, Tversky, and Hazeltine (2002) showed a correlation between object-based transformations and psychometric tests of spatial visualization that required same/different judgments of asymmetric picture pairs. The disparity in the orientation of the pairs was varied from trial-to-trial and participants were to judge whether the pictures were identical or mirror images. There was also a correlation between egocentric transformations and psychometric tests of spatial orientation, which require left/right judgments of a single asymmetric picture. Again, the orientation of an image is varied from trial-to-trial and participants have to make a handedness judgment (e.g., whether a figure's outstretched arm is a left or right arm). The influence of spatial ability factors has not, however, been examined with respect to effector-based transformations. It is assumed that each transformation can vary independently across individuals. Differences in performance on tasks that tap these different transformations will be pronounced in individuals whose spatial ability reflects advantages in spatial orientation, spatial visualization, and/or kinesthetic imagery as reflective in their chronometric profiles (i.e., response times in tasks tapping each type of mental transformation differ as a function of different processing systems).

The aim of this study is to test whether effector-based transformations require the ability of spatial orientation, of spatial visualization, or of kinesthetic imagery. Existing research using 2D images of bodies has shown that object-based transformations are recruited for a same/different task and that perspective transformations are recruited for a left/right task (Zacks, Mires, et al., 2002). Effector-based transformations have been previously studied using a left/right task and a same/different task with 2D images of hand stimuli with mixed results as to whether effector-based transformations require separate mechanisms (Kosslyn, et al., 1998; Parsons, 1987b; Wraga, Thompson, Alpert, & Kosslyn, 2003). Participants will complete psychometric tests of the three spatial ability factors as well as perform desktop computer-based spatial transformation tasks that measure reaction time and accuracy. First, I will use the psychometric tests to determine the factor structures with a confirmatory factor analysis (CFA). Second, I will use the resulting factor scores to test specific predictions of the processes recruited as a function of the different stimuli (bodies and hands and feet) and the task required (same/different and left right). Specifically I will test whether spatial orientation, spatial visualization, or kinesthetic imagery predicts performance on effector-based transformations and whether this is modulated by the type of task. In addition, I will use the factor scores of spatial orientation and spatial visualization to test if there is further support for the claim that egocentric transformations underlie left/right tasks and object-based transformations support same/different tasks with bodies. Finally, I will compare RT performance across bodies and effectors for each type of task to test whether there is evidence for similar or different response time functions, suggestive of similar or different underlying transformation mechanisms.

Method

Participants

A total of 112 young adults participated from the University of Utah psychology undergraduate participant pool. Twelve participants were excluded because of methodological issues (e.g., did not follow instructions or computer program errors), 2 participants were excluded because of physical limitations that did not allow them to complete the MIQ-RS, and 3 participants were excluded because of greater than chance error. Each of the 95 participants (37 males, 58 females, mean age 21.42 years) completed a battery of psychometric tests and computer-based tasks during a testing session that lasted approximately 2 hours. Participants were compensated with credit towards a psychology course requirement or for extra credit. All participants had normal or corrected-to-normal vision.

Materials

The materials consisted of six psychometric tests of spatial ability and four computer-based spatial transformation tasks. Spatial orientation ability was measured with the Perspective Taking/Spatial Orientation Test (SOT; Hegarty & Waller, 2004) and Money's Road-Map Test of Direction Sense (MRM; Money, Alexander, & Walker, 1965). In the SOT participants were shown a 2D drawing of seven objects. They were asked to imagine themselves standing at one of the objects while facing another object and then tasked to indicate the location of a third object relative to the imagined position. The MRM required the participant to view a map with an elaborate path drawn and then indicate right or left turns along the path from a pedestrian's perspective. Spatial visualization ability was measured with the Paper Folding Test (PFT; Ekstrom, et al., 1976) and the Cube Comparison Test (CCT; Ekstrom, et al., 1976). In the PFT, participants were presented with a series of drawings of a folded square sheet of paper where the last drawing shows a hole punched through the entirety of the sheet. Participants had to choose one from five options of what the punched sheet would look like when completely opened. In the CCT, the participant had to decide whether two cubes are the same or different based on the assumption that no two faces are alike. Kinesthetic imagery ability was measured with the Movement Imagery Questionnaire Revised Second Version (MIQ-RS; Gregg, Hall, & Butler, 2007) and the revised Vividness of Movement Imagery Questionnaire (VMIQ-2; Roberts, Callow, Hardy, Markland, & Bringer, 2008) . The MIQ-RS is a questionnaire that evaluates two ways of imaging performing movement – visual and kinesthetic. The VMIQ-2 is a questionnaire that assesses the vividness of a participant's ability to visually imagine movement from a first person perspective and a third person perspective as well as the ability to kinesthetically imagine movement.

The computer-based transformation tasks were based on paradigms traditionally used to test the different transformations. Object-based transformations are typically evaluated using same/different judgments such as in Shepard and Metzler's mental rotation paradigm. Perspective transformations are typically evaluated using left/right judgments such as in mental body rotation tasks (MBRT) where participants have to make a viewer based judgment given a perspective rotation. Effector-based transformations are typically evaluated using left/right judgments such as in mental body part rotation tasks where participants have to make a body specific judgment given a body part rotation. Within these paradigms, biological objects, as opposed to objects, letters or abstract figures, have been used successfully to elicit the use of a specific type of transformation. In this study, the stimuli consisted of hands, feet, and whole bodies rotated in the picture plane or the axial plane. The whole body avatar was from the WorldVis Vizard Complete Characters Library and the hands and feet were purchased from the website Turbo Squid. Manipulations of the avatar, hands and feet were done in Autodesk 3ds Max 2012. E-prime 2.0 was used to display the tasks and keyboard presses collected participant responses. Based on availability and ease of access, three different computer monitors (1: Resolution 1600 x 1200 UXGA, Physical size 41cm x 31cm; 2: Resolution 1680 x 1050 WSXGA, Physical size 47.5cm x 30cm; 3: Resolution 1920 x 1080 FHD, Physical size 47.5cm x 27cm) were used to display the stimuli sized to accommodate the smallest height in terms of resolution of the three monitors. The approximate visual angle of the body stimuli was 8.53° and 4.76° for effector stimuli.

Computer-based Design

A 2 (stimuli) x 2 (task) x 2 (axis) x 6 (degree) x 2 (condition) x 2 (view) factorial design in which stimuli (bodies or body parts), task (same/different or left/right), axis (picture plane or axial plane), degree (0, 60, 120, 180, 240, and 300 degrees), condition (bodies with arms outstretched or arms across their body; hands or feet) and view (front or back of stimuli; upright or inverted) are within-subjects variables. Two types of three-dimensional stimuli were used – whole bodies (see Figure 1), and body parts (i.e., hands

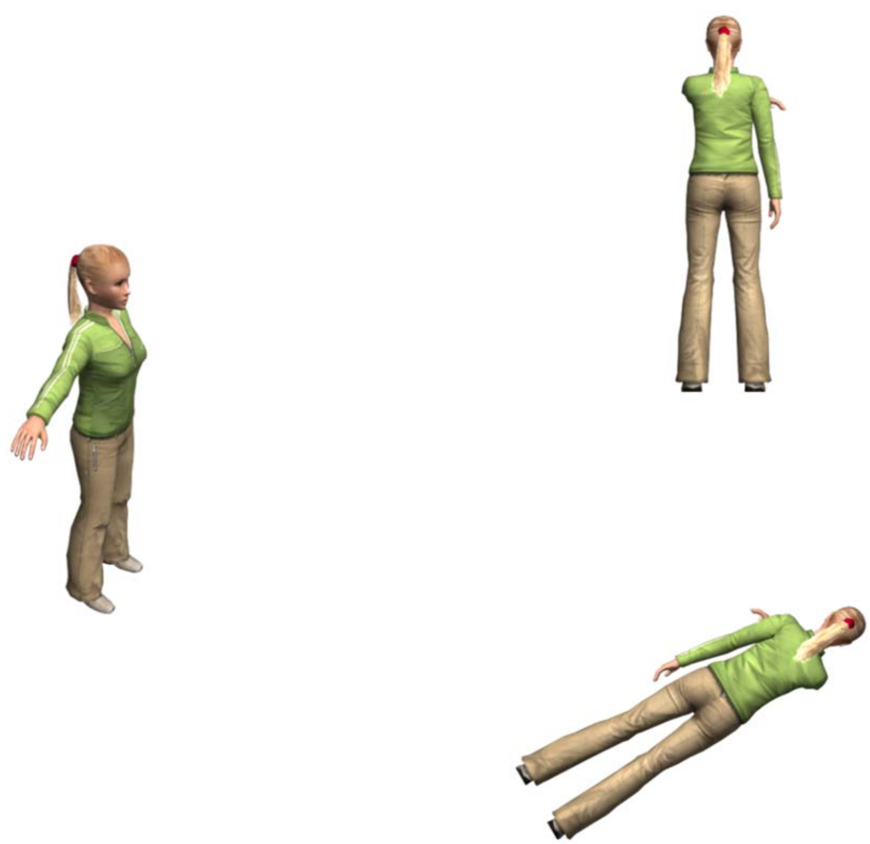

Figure 1. Body Stimuli as Presented in Each Task. Left/right task with body stimuli with arm outstretched and rotated in the axial plane (*left*); Same/different task with body stimuli with arm across body and rotated in the picture plane (*right*).

and feet; see Figure 2). In the same/different task, participants were presented with a pair of images and asked to judge whether the images were of the same object but rotated, or of different objects (i.e., mirror image). In the left/right task, participants were presented with an image and asked to judge whether the body had a left or right arm extended, or if a body part was a left or right hand or foot. Participants completed eight blocks of experimental trials (768 total trials) where there were four trials (two repetitions of stimuli of each laterality) per 192 different combinations. Trials were presented in blocks

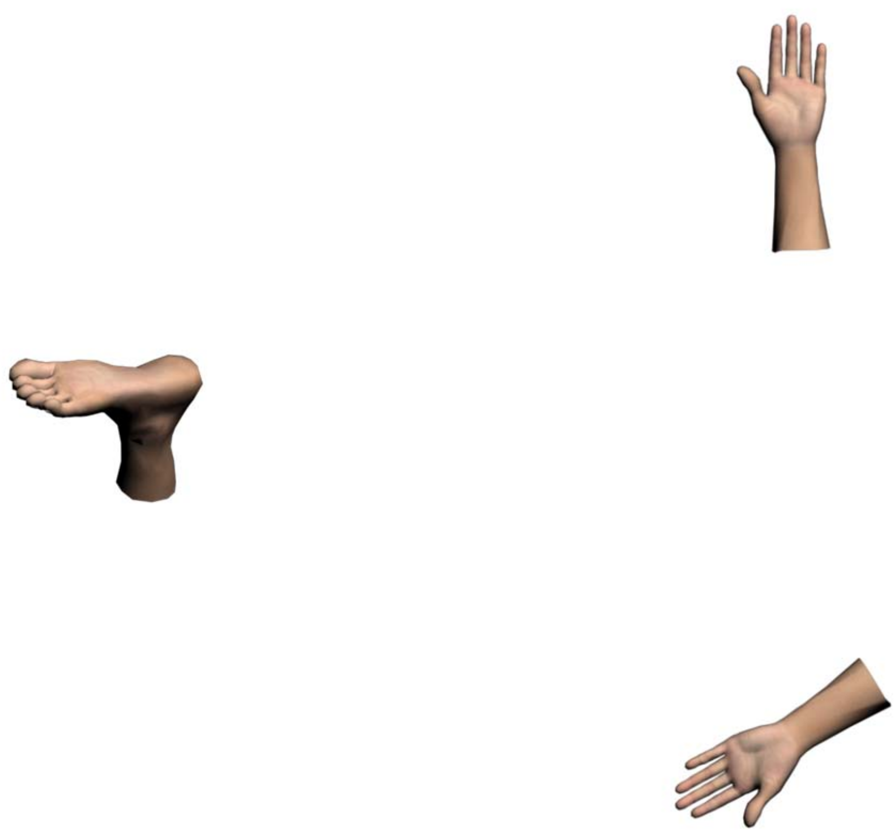

Figure 2. Effector Stimuli as Presented in Each Task. Left/right task with effector stimuli with inverted foot rotated in the axial plane (*left*); Same/different task with effector stimuli with bottom of the hand rotated in the picture plane (*right*).

in a 2 (stimuli) x 2 (task) x 2 (axis) design that were pseudo-randomized such that participants completed all of the blocks for a given axis of rotation first. On each trial, a blank black screen with a fixation cross was presented for 500 ms followed by an image centered in a black screen for the L/R task (see Figures 1 and 2) or two images vertically aligned with the center of a black screen for the S/D task (see Figures 1 and 2). The image(s) remained on the screen for 12000 ms or until the participant made a response.

Procedure

Informed consent was obtained. Following consent, all participants completed eight computer-administered spatial transformation tasks. Participants did four blocks of the same/different (S/D) task and four blocks of the left/right (L/R) task corresponding with the two different rotation planes and two types of stimuli (e.g., L/R with bodies rotated in the picture plane, L/R with effectors rotated in the picture plane, L/R with bodies rotated in the axial plane, and L/R with effectors rotated in the axial plane; see Figures 1 and 2 and Appendices A and B). The presentation of the computer-based tasks were counter-balanced and randomized across participants. At the start of every block, participants were given verbal instructions and then shown four examples of the stimuli. Participants were instructed to keep a finger from each hand on the response keys, to not move their body, and to keep their feet firmly planted on the ground in order to prevent the use of any part of their bodies in making judgments. The participant then did 10 practice trials with no feedback, while the experimenter watched. The experimenter only gave feedback if it appeared that the participant incorrectly mapped the responses on the keyboard number pad (1 = same/left; 2 = different/right). The participant then completed a block of trials with a 1-minute break in the middle. After the block was over, the experimenter came back and loaded the next block of trials. The computer tasks took approximately 1 hour to complete. All participants then completed a general questionnaire followed by a battery of spatial abilities tests including spatial orientation tests, spatial visualization tests, and kinesthetic imagery tests. The order of presentation for the psychometric tests was counter-balanced and pseudo-randomized across participants. The psychometric tests took approximately 1 hour to complete. At the end of the experiment, participants were debriefed.

Results

Coding

The psychometric test scores were parceled for the purpose of the confirmatory Factor Analysis (CFA). The SOT score was the average error across all trials. The MRM was scored so that each correct response was given 1 point and every incorrect response was given 0 points. The MRM contained 32 turns with 8 types of turns and 4 trials of each turn type. Two scores were created by evenly dividing the turns so that each type of turn was represented twice in each score, where one turn was taken from the beginning half of the test and the other turn was taken from the last half of the test. The PFT score was scored so that each correct response was given 1 point and every incorrect response was given -0.75 points. The PFT is a two-part test with each part resulting in a separate score. The CCT score was scored so that each correct response was given 1 point and every incorrect response was given -1 points. The CCT is a two-part test with each part resulting in a separate score. The MIQ-RS score is the sum of the participant's ratings for the visual imagery measures (MIQ-VIS) and the sum of their ratings for the kinesthetic imagery measures (MIQ-KIN), resulting in two scores. The VMIQ-2 score is the sum of the participant's ratings for the first-person visual imagery measures (IVI), the sum of the participant's ratings for the third-person visual imagery measures (EVI), and the sum of the participant's ratings for the kinesthetic imagery measures (KIN), resulting in three scores. The raw psychometric test scores were then used the CFA.

The raw data from the computer task consisted of reaction time (RT) for each trial recorded in milliseconds. The raw data from E-Prime were then compiled into mean RT for correct responses only for each of the 192 possible combinations in Matlab R2011a.

Analyses

A CFA was performed using AMOS 20 statistical package on the parceled psychometric tests scores to confirm that the test scores are representative of three distinct factors. CFA factor scores were then used in repeated measures ANOVA to predict RT performance on the computer-based tasks. Missing RT data cells were replaced with the sample average for that cell. A total of .71% of the cells was replaced.

Results

CFA. Table 1 shows the correlations between the parceled psychometric tests. The measures of SV (PFT, CCT) are highly correlated with each other as are the measures of SO (SOT, MRM) and KI (MIQ-RS, VMIQ-2). Additionally all of the measures of SV and the measures of SO are significantly correlated consistent with previous studies (e.g., Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001). Interestingly, the visual portion of the MIQ-RS is negatively correlated with SOT, $r(95) = -0.227$, $p = .013$, as the SOT is an average error score where a higher score equates to less ability. Additionally, MIQ-VIS is positively correlated with a first section of MRM,

Table 1

Correlations Between Psychometric Tests (Pearson Correlation Coefficients, N=95)

Task	PFT 1	PFT 2	CCT 1	CCT 2	SOT	MRM 1	MRM 2	MIQ VIS	MIQ KIN	VMIQ-2 IVI	VMIQ-2 EVI	VMIQ-2 KIN
PFT 1	–	.696**	.571**	.574**	-.449**	.344**	.354**	.072	-.054	-.091	.108	.047
PFT 2		–	.473**	.477**	-.332**	.226*	.184*	.026	-.002	-.021	.126	.142
CCT 1			–	.655**	-.413**	.297**	.300**	-.031	.031	-.048	.078	.110
CCT 2				–	-.439**	.269**	.329**	.037	-.103	.036	.109	.057
SOT					–	-.454**	-.433**	-.173*	-.100	.083	.067	.068
MRM 1						–	.721**	.186*	.081	-.129	-.086	-.191*
MRM 2							–	-.109	.098	-.119	-.109	-.112
MIQ-RS VIS								–	.475**	-.364**	-.357**	-.412**
MIQ-RS KIN									–	-.301**	-.277**	-.522**
VMIQ-2 IVI										–	.571**	-.301**
VMIQ-2 EVI											–	.470**

Note. PFT: Paper Folding Test. CCT: Cube Comparisons Test. SOT: Spatial Orientation Test. MRM: Money's Road Map Test. MIQ-RS: Movement Imagery Questionnaire Second Revision. VMIQ-2: Revised Vividness of Movement Imagery Questionnaire. $*p < .05$. $**p < .01$.

$r(95) = .185$, $p = .037$, and trending for the second section of the MRM, $r(95) = .167$, $p = .053$. These findings suggest a relationship between the visual portion of the MIQ-RS and SO. Finally, the kinesthetic section of the VMIQ-2 is negatively correlated with the first section of the MRM, $r(95) = -0.205$, $p = .023$, as a lower score on the VMIQ-2 corresponds to better performance.

According to the three-factor model (see Figure 3), there are three distinct spatial ability factors – spatial visualization (SV), spatial orientation (SO), and kinesthetic imagery (KI). It was assumed that the two subtest scores of PFT and the two subtest scores from CCT would load on the latent variable SV, that SOT and the two parcel scores of MRM would load on SO, and that MIQ-VIS, MIQ-KIN, IVI, EVI, and KIN would load on KI given that the high correlation between spatial factor related tests. The model produced a significant $\chi^2(51) = 80.509$, $p=0.005$, indicating that the model significantly deviates from the data and is not a good fit. However this could be due to a lack of statistical power because of the small sample size ($n=95$). Other measures of fit do show acceptable model fit. The root-mean-square error of approximation (RMSEA) statistic is .077, which meets the criterion (<0.08) for acceptable fit. The Comparative Fit Index (CFI) is .929, which meets the criterion (>0.9) for acceptable fit. To compare the fit of the three-factor model, I also tested two alternative two-factor models where the subtest scores from the MIQ-RS and VMIQ-2 either loaded on SO (see Figure 4) or SV (see Figure 5). The chi-squared for the two-factor model loading on SO was significant with $\chi^2(53) = 196.392$, $p<0.001$ indicating a bad fit. The root mean residual (RMR) was 11.800 and the Bayes Information Criterion (BIC) for this two-factor model is 311.016. The chi-squared for the two-factor model loading on SV was also significant with $\chi^2(53)$

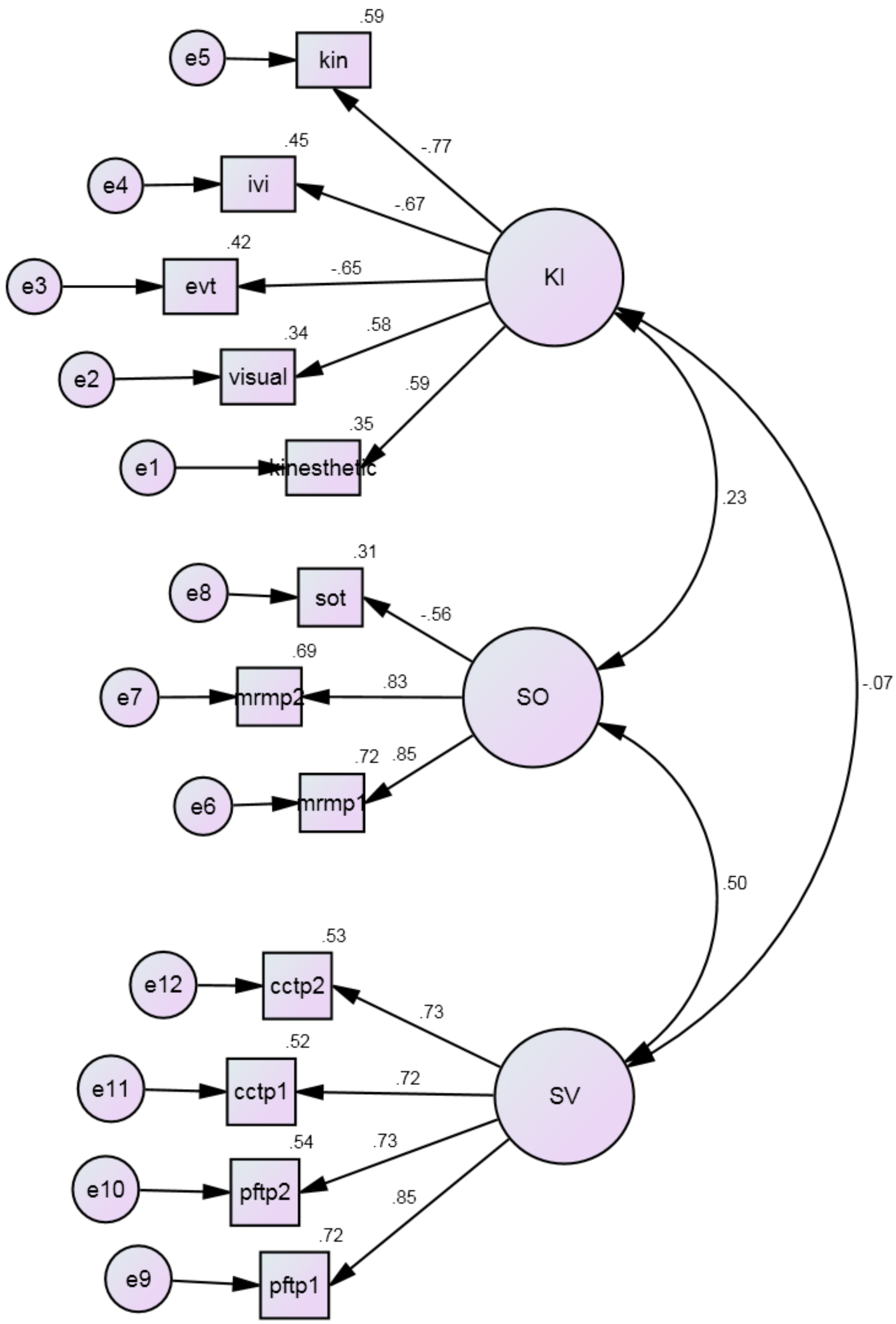

Figure 3. Three-Factor Model of Spatial Ability.

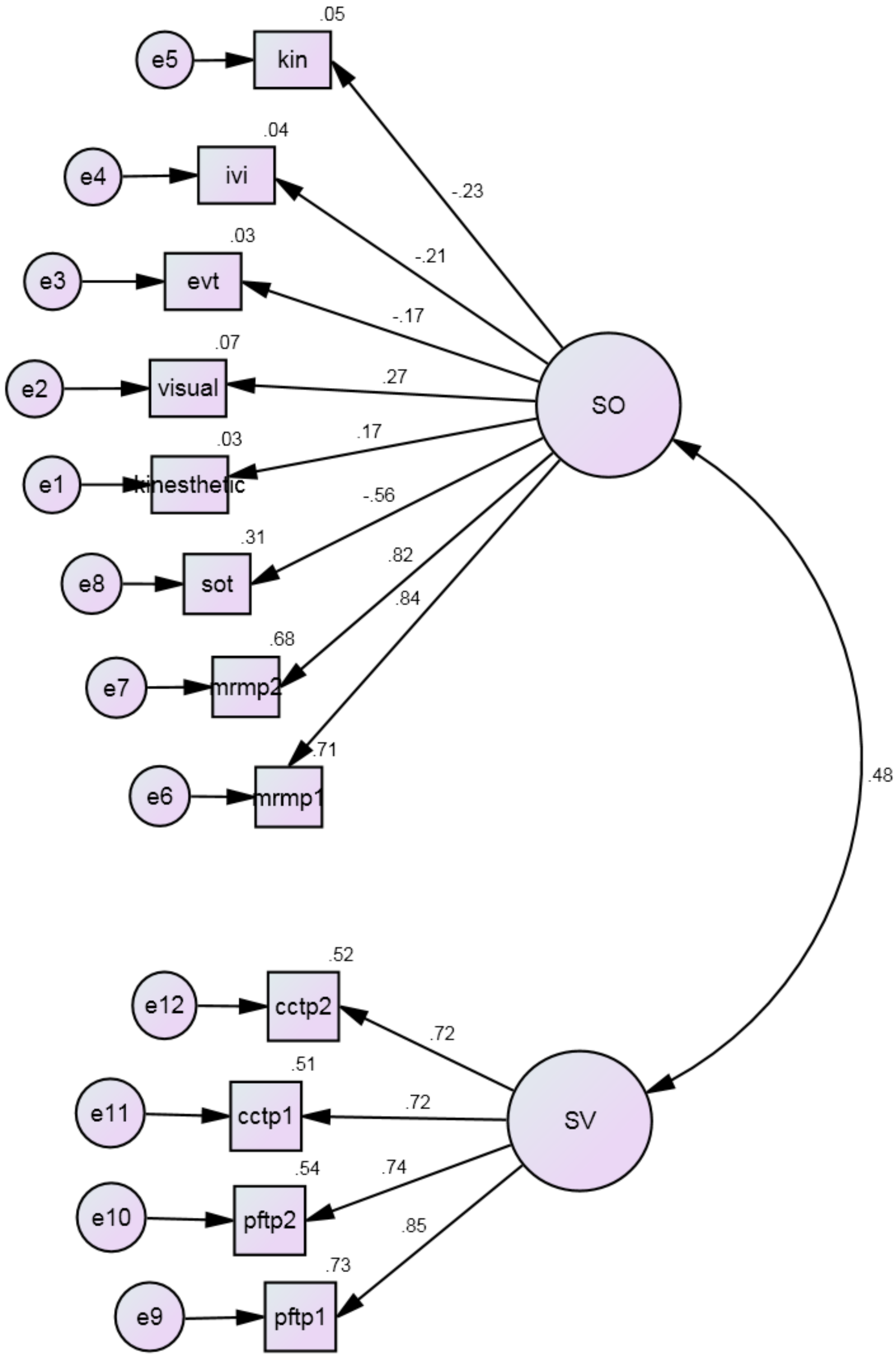

Figure 4. Two-Factor Model of Spatial Ability with MIQ-RS and VMIQ-2 Predicted to load on SO.

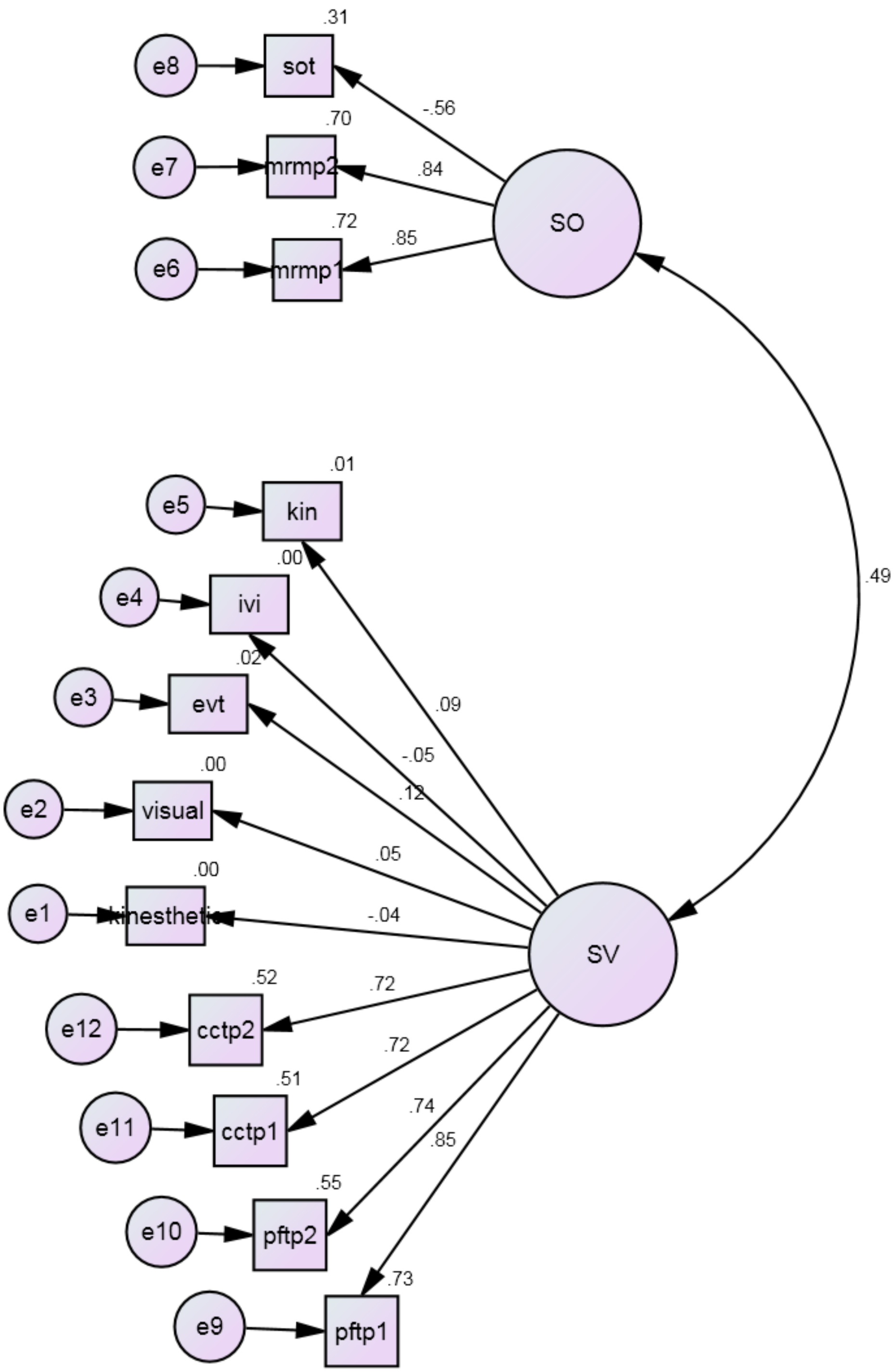

Figure 5. Two-Factor Model of Spatial Ability with MIQ-RS and VMIQ-2 Predicted to load on SV.

= 206.968, *p*<0.001 indicating bad fit. This two-factor model had a RMR of 13.670 and a BIC of 321.592. In comparison, the three-factor model had the smallest RMR with 7.461 and the smallest BIC with 204.303, where smaller is better for both statistics in terms of model fit. In sum based on the fit indices the three-factor model has the best fit of the models and is acceptable fit for the observed data.

Spatial Ability and Transformations

To test whether spatial ability predicts spatial transformation performance, separate analyses were done for each task, stimulus type, and axis of rotation combination in order to test specific hypotheses. Previous research has shown that the chronometric profiles for the L/R task and the S/D task differ for picture plane rotations compared to axial plane rotations (Parsons, 1987a; Zacks, Mires, et al., 2002). Differences may be due to the extent that key information is visible (such as the extended arm for body judgments) when rotating a stimulus in the picture plane v. the axial plane (see Figure 1 and Appendix A). A 6 (degree) x 2 (condition) x 2 (view) ANOVA was performed on mean RT with degree, condition and view as within-subjects variables, and the CFA factor scores for spatial ability (SV, SO, and KI) as covariates. Only findings specific to stated hypotheses will be discussed.[1]

Picture Plane Rotations

For the L/R task for bodies rotated in the picture plane (see Table 2 and Figure 6), there was an overall main effect of KI ($F_{1,91} = 4.812$, $p = .031$; $\eta_p^2 = .050$) but not of SO ($F_{1,91} = .073$, $p = .788$; $\eta_p^2 = .001$) as might have been expected based on previous

[1] All significant and nonsignificant effects are included in the Tables 2-9.

Table 2

Analysis of Variance on Average RT for L/R Task with Bodies Rotated in the Picture Plane and Factor Scores as Covariates

	df	*F*	η	*p*
degree	5	1.197	.013	.310
condition (across, out)	1	.410	.004	.524
view	1	1.155	.013	.285
degree x condition	5	3.375**	.036	.005
degree x view	5	1.209	.013	.304
condition x view	1	2.342	.025	.129
degree x condition x view	5	1.612	.017	.155
SV	1	2.089	.022	.152
SO	1	.073	.001	.788
KI	1	4.812*	.050	.031

Note. *p < .05. **p < .01. ***p < .001.

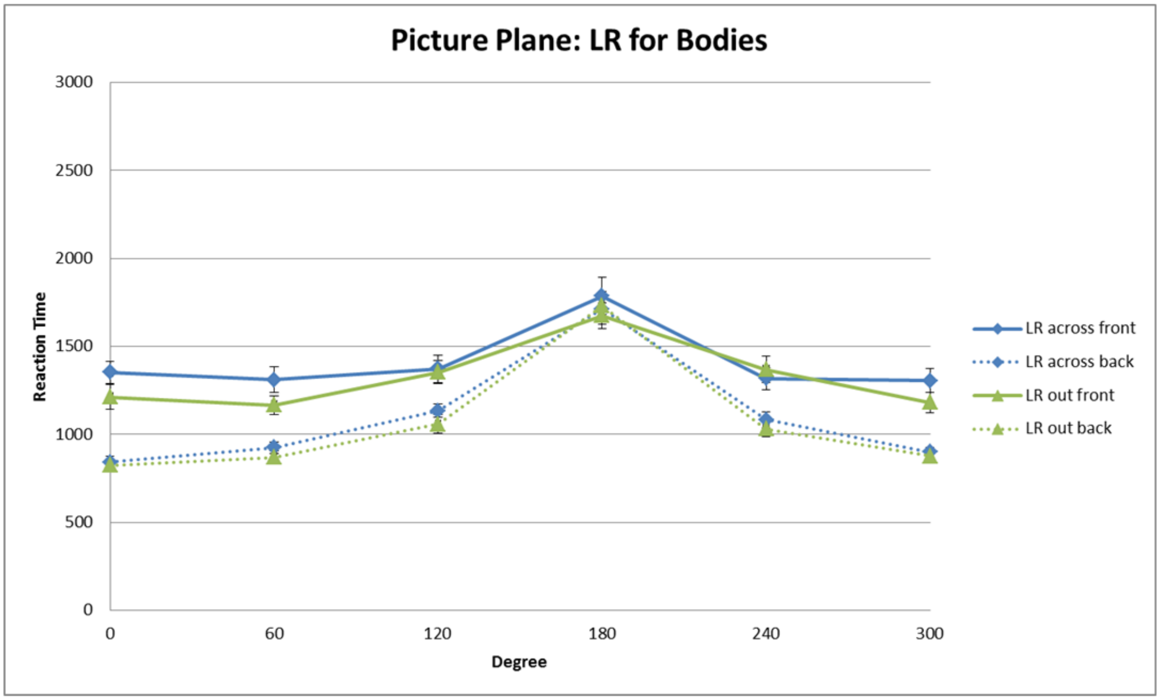

Figure 6. Reaction Time Profiles for the Left/Right Task for Body Stimuli by Condition and View Rotated in the Picture Plane. Error bars represent -/+ 1 SEM.

findings (Zacks & Michelon, 2005). As predicted, there was no main effect of degree ($F_{5,455} = 1.197$, $p = .310$; $\eta_p^2 = .013$), showing that overall RT did not differ as the degree of rotation of the stimulus increased. Although the RT functions appear to change as a function of degree and view (i.e., front or back of body), it appears that the strong KI covariate accounts for these effects.[2] However, the flatter RT profile for the front view of bodies and the somewhat steeper linear increase for the back view of bodies are consistent with some previous studies (Jola & Mast, 2005; Schönenberger, Long, Ryf, Mast, & Schwaninger, 2006; Steggemann, Engbert, & Weigelt, 2011).

For the S/D task for bodies rotated in the picture plane (see Table 3 and Figure 7), there was an overall main effect of SV ($F_{1,91} = 8.13$, $p = .005$; $\eta_p^2 = .082$) replicating previous findings (Zacks & Michelon, 2005). As predicted, there was a significant main effect of degree ($F_{5,455} = 6.542$, $p < .001$; $\eta_p^2 = .067$), indicating a monotonically

Table 3

Analysis of Variance on Average RT for S/D Task with Bodies Rotated in the Picture Plane and Factor Scores as Covariates

	df	*F*	η	*p*
degree	5	6.542***	.067	< .001
condition (across, out)	1	3.339	.035	.071
view	1	1.054	.011	.307
degree x condition	5	.598	.007	.701
degree x view	5	.286	.003	.921
condition x view	1	.368	.004	.546
degree x condition x view	5	1.913	.021	.091
SV	1	8.135**	.082	.005
SO	1	1.133	.012	.290
KI	1	.358	.004	.551

Note. *p < .05. **p < .01. ***p < .001.

[2] Statistical analysis without the covariates shows the apparent degree and view effects. See Table 10.

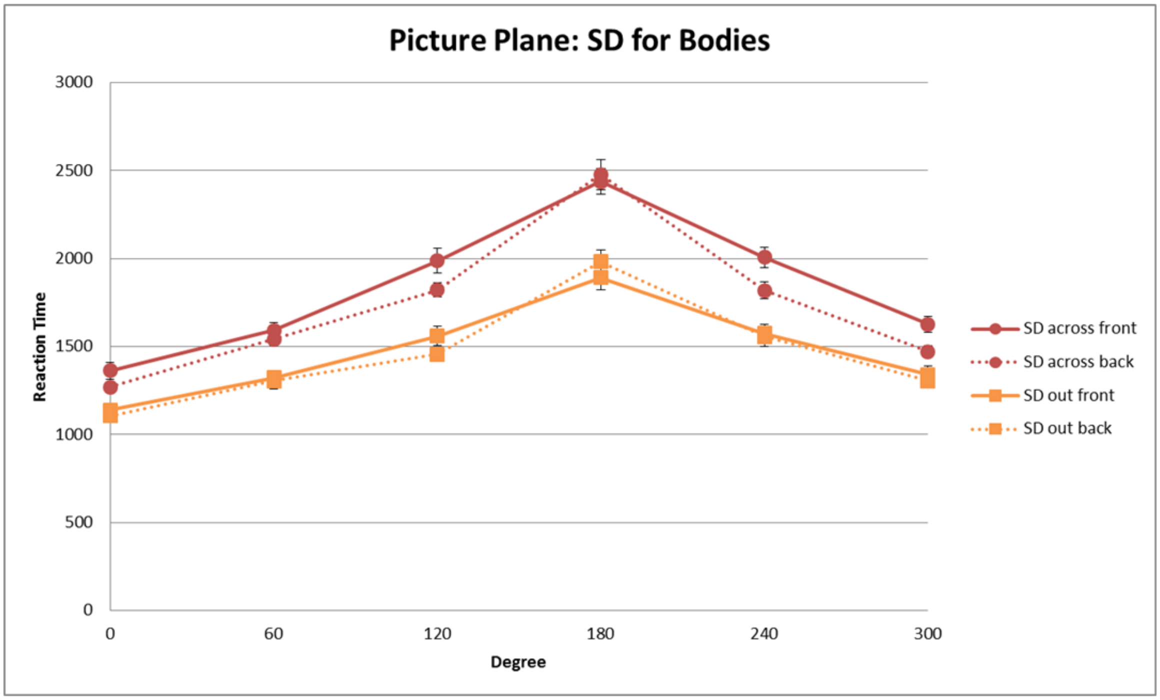

Figure 7. Reaction Time Profiles for the Same/Different Task for Body Stimuli by Condition and View Rotated in the Picture Plane. Error bars represent -/+ 1 SEM.

increasing RT function as degree of rotation increased to 180 degrees.

For the L/R task for body parts rotated in the picture plane (see Table 4 and Figure 8), there was a main effect of KI ($F_{1,91} = 4.023$, $p = .048$; $\eta_p^2 = .042$) but no effect for SO ($F_{1,91} = .019$, $p = .891$; $\eta_p^2 < .001$) suggesting that L/R judgments for body parts are processed similarly as bodies. There was no effect of degree ($F_{5,455} = .223$, $p = .953$; $\eta_p^2 = .002$) or of condition (hands v. feet; $F_{1,91} = .699$, $p = .405$; $\eta_p^2 = .008$). Again, although the RT functions appear to change as a function of degree and type of effector, it appears that the strong KI covariate accounts for these effects.[3]

For the S/D task for body parts rotated in the picture plane (see Table 5 and Figure 9), there was a main effect of SO ($F_{1,91} = 4.871$, $p = .030$; $\eta_p^2 = .051$) but no effect of SV ($F_{1,91} = 1.600$, $p = .209$; $\eta_p^2 = .017$) or KI ($F_{1,91} = .117$, $p = .733$; $\eta_p^2 = .001$)

[3] Statistical analysis without the covariates shows the apparent degree and effector effects. See Table 11.

Table 4

Analysis of Variance on Average RT for L/R Task with Effectors Rotated in the Picture Plane and Factor Scores as Covariates

	df	*F*	η	*p*
degree	5	.223	.002	.953
condition (hands, feet)	1	.699	.008	.405
view	1	.007	< .001	.933
degree x condition	5	.659	.007	.655
degree x view	5	.570	.006	.723
condition x view	1	.466	.005	.496
degree x condition x view	5	.740	.008	.594
SV	1	1.281	.014	.261
SO	1	.019	< .001	.891
KI	1	4.023*	.042	.048

Note. *p < .05. **p < .01. ***p < .001.

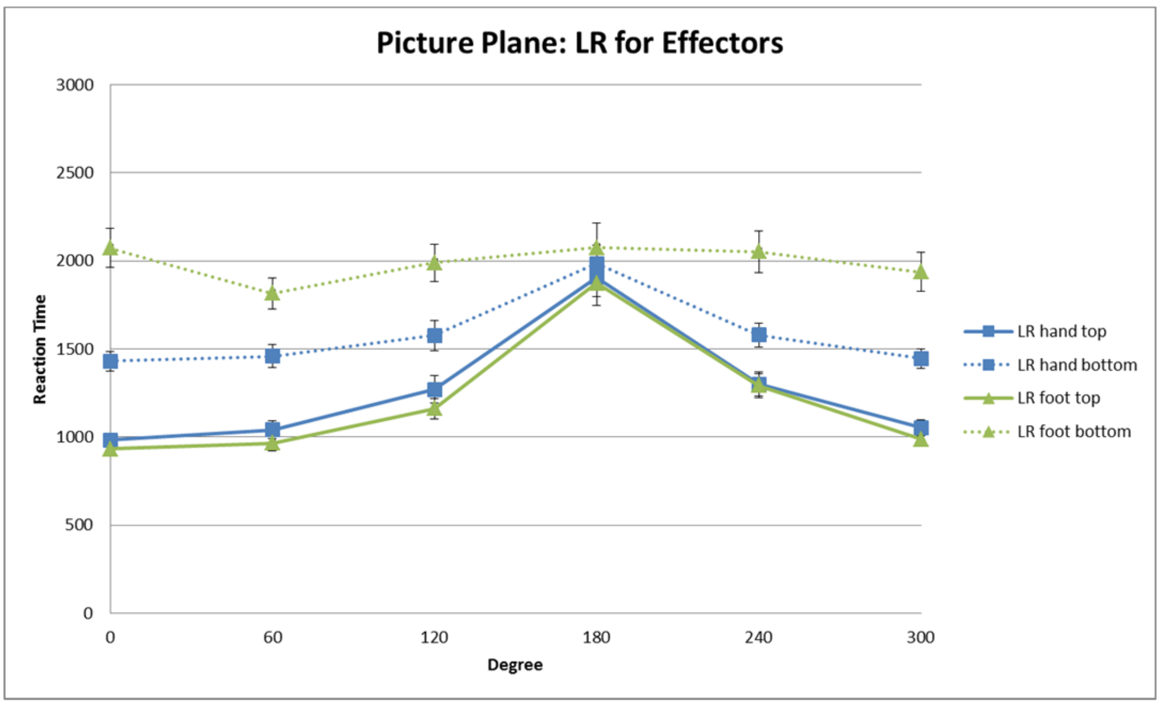

Figure 8. Reaction Time Profiles for the Left/Right Task for Effector Stimuli by Condition and View Rotated in the Picture Plane. Error bars represent -/+ 1 SEM.

Table 5

Analysis of Variance on Average RT for S/D Task with Effectors Rotated in the Picture Plane and Factor Scores as Covariates

	df	*F*	η	*p*
degree	5	7.493***	.076	< .001
condition (hands, feet)	1	2.142	.023	.147
view	1	.156	.002	.694
degree x condition	5	1.367	.015	.235
degree x view	5	2.019	.022	.075
condition x view	1	.034	< .001	.853
degree x condition x view	5	4.711***	.049	< .001
SV	1	1.600	.017	.209
SO	1	4.871*	.051	.030
KI	1	.117	.001	.733

Note. *$p < .05$. **$p < .01$. ***$p < .001$.

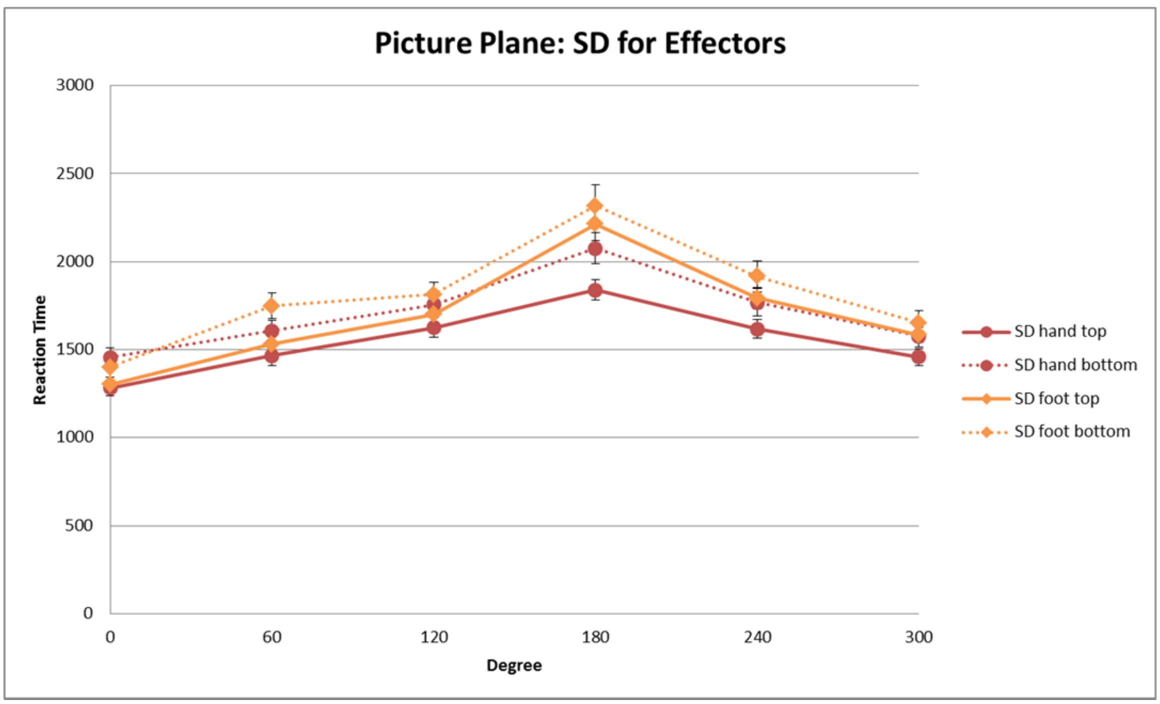

Figure 9. Reaction Time Profiles for the Same/Different Task for Effector Stimuli by Condition and View Rotated in the Picture Plane. Error bars represent -/+ 1 SEM.

suggesting that same/different judgments of effectors are processed differently than same/different judgments of bodies. There was a significant main effect of degree ($F_{5,455}$ = 7.493, p < .001; η_p^2 = .076) but no effect of condition ($F_{1,91}$ = 2.142, p = .147; η_p^2 = .023), indicating that RT increased as the degree of rotation increased to 180 degrees but there was no difference based on effector type. There was a degree x condition x view interaction ($F_{5,455}$ = 4.711, p < .001; η_p^2 = .049) showing that participants were faster responding to the tops of effectors than bottoms across degrees of rotation and faster at responding to hands than feet.

Axial Plane Rotations

For the L/R task for bodies rotated in the axial plane (see Table 6 and Figure 10), there were no main effects of spatial ability. There was a main effect of degree ($F_{5,455}$ = 5.111, p < .001; η_p^2 = .053), but not of view ($F_{5,455}$ = 2.241, p =.138; η_p^2 = .024) driven by a significant difference in RT for bodies at the 0 degree position (facing the participant) compared to the 60 degree position. Although the RT functions appear to change as a function of view, an analysis without the covariates reveals a significant main effect of view.[4]

For the S/D task for bodies rotated in the axial plane (see Table 7 and Figure 11), there is a main effect of SV ($F_{1,91}$ = 10.217, p = .002; η_p^2 = .101) as predicted. There was a main effect of degree ($F_{5,455}$ = 4.954, p < .001; η_p^2 = .052) indicating that RT differed as degree of rotation increases. There was also a main effect of view ($F_{5,455}$ = 5.312, p = .023; η_p^2 = .055) suggesting that judgments of bodies that are upside down took longer than bodies that were right side up.

[4] Statistical analysis without the covariates shows the apparent view effect. See Table 12.

Table 6

Analysis of Variance on Average RT for L/R Task with Bodies Rotated in the Axial Plane and Factor Scores as Covariates

	df	*F*	η	*p*
degree	5	5.111***	.053	< .001
condition (across, out)	1	2.468	.026	.120
view	1	2.241	.024	.138
degree x condition	5	1.646	.018	.146
degree x view	5	1.503	.016	.188
condition x view	1	.342	.004	.560
degree x condition x view	5	1.763	.019	.119
SV	1	1.214	.013	.274
SO	1	.990	.011	.322
KI	1	1.395	.015	.241

Note. **p* < .05. ***p* < .01. ****p* < .001.

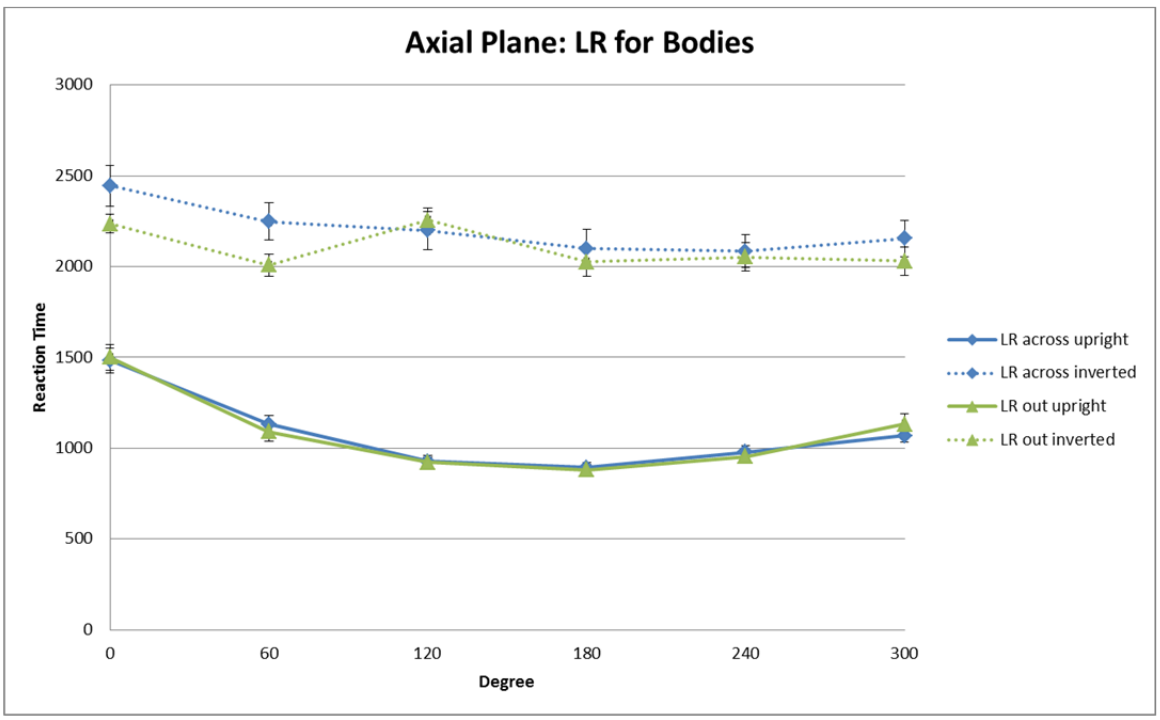

Figure 10. Reaction Time Profiles for the Left/Right Task for Body Stimuli by Condition and View Rotated in the Axial Plane. Error bars represent -/+ 1 SEM.

Table 7

Analysis of Variance on Average RT for S/D Task with Bodies Rotated in the Axial Plane and Factor Scores as Covariates

	df	*F*	η	*p*
degree	5	4.954***	.052	< .001
condition (across, out)	1	.528	.006	.469
view	1	5.312*	.055	.023
degree x condition	5	.525	.006	.757
degree x view	5	.858	.009	.510
condition x view	1	1.982	.021	.163
degree x condition x view	5	.980	.011	.430
SV	1	10.217**	.101	.002
SO	1	.442	.005	.508
KI	1	.001	< .001	.980

Note. **p* < .05. ***p* < .01. ****p* < .001.

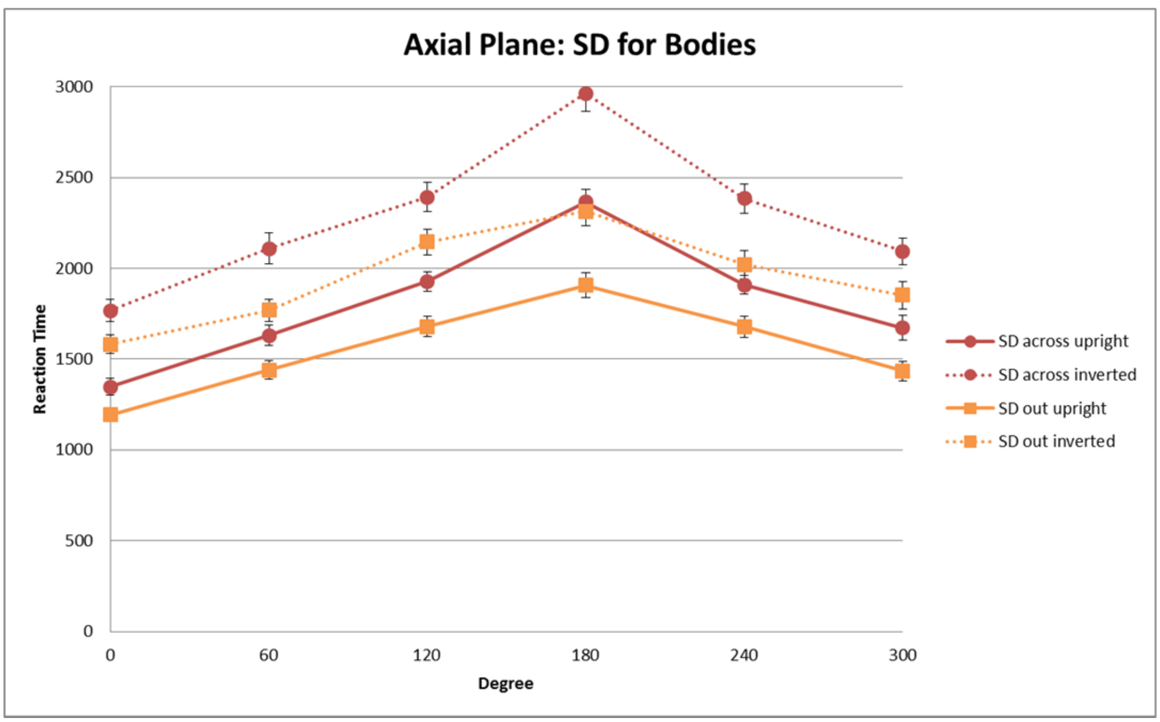

Figure 11. Reaction Time Profiles for the Same/Different Task for Body Stimuli by Condition and View Rotated in the Axial Plane. Error bars represent -/+ 1 SEM.

For the L/R task for body parts rotated in the axial plane (see Table 8 and Figure 12), there was a main effect of SO ($F_{1,91} = 7.623$, $p = .007$; $\eta_p^2 = .077$) but no effect of KI ($F_{1,91} = .520$, $p = .473$; $\eta_p^2 = .006$). This is contrary to predictions but consistent with previous studies where left/right judgments require SO. There was a significant main effect of degree ($F_{5,455} = 2.879$, $p = .014$; $\eta_p^2 = .031$), which seems to be driven by a significant difference between effectors positioned at 240 degrees and 300 degrees, two biomechanically difficult positions. There was also a significant main effect of view ($F_{5,455} = 7.372$, $p = .008$; $\eta_p^2 = .075$) where judgments of upside down effectors had slower RT than right side up. There was a degree x condition interaction ($F_{5,455} = 2.412$, $p = .036$; $\eta_p^2 = .026$) where hands show a steeper RT profile than feet and a degree x view interaction ($F_{5,455} = 9.149$, $p <.001$; $\eta_p^2 = .091$) where right side up effectors show a steeper RT profile than upside down effectors.

For the S/D task for body parts rotated in the axial plane (see Table 9 and Figure 13), there is a main effect of SO ($F_{1,91} = 12.595$, $p = .001$; $\eta_p^2 = .122$) but not of KI ($F_{1,91} = 1.667$, $p = .200$; $\eta_p^2 = .018$) as predicted suggesting that effectors rotated in the axial plane tap similar processes as effectors rotated in the picture plane. There is a main effect of degree ($F_{5,455} = 3.552$, $p = .004$; $\eta_p^2 = .038$) as predicted. There was also a main effect of view ($F_{5,455} = 16.777$, $p < .001$; $\eta_p^2 = .156$) where upside down effectors had slower RT than right side up.

Chronometric Profiles

To test whether there is evidence for similar or different response time functions across each task and stimulus type, an ANOVA was performed on mean RT, including task as an independent variable without the inclusion of the spatial ability covariates. For

Table 8

Analysis of Variance on Average RT for L/R Task with Effectors Rotated in the Axial Plane and Factor Scores as Covariates

	df	*F*	η	*p*
degree	5	2.879*	.031	.014
condition (hands, feet)	1	.224	.002	.637
view	1	7.372**	.075	.008
degree x condition	5	2.412*	.026	.036
degree x view	5	9.149***	.091	< .001
condition x view	1	1.540	.017	.218
degree x condition x view	5	1.568	.017	.168
SV	1	.303	.003	.584
SO	1	7.623**	.077	.007
KI	1	.520	.006	.473

Note. *p < .05. **p < .01. ***p < .001.

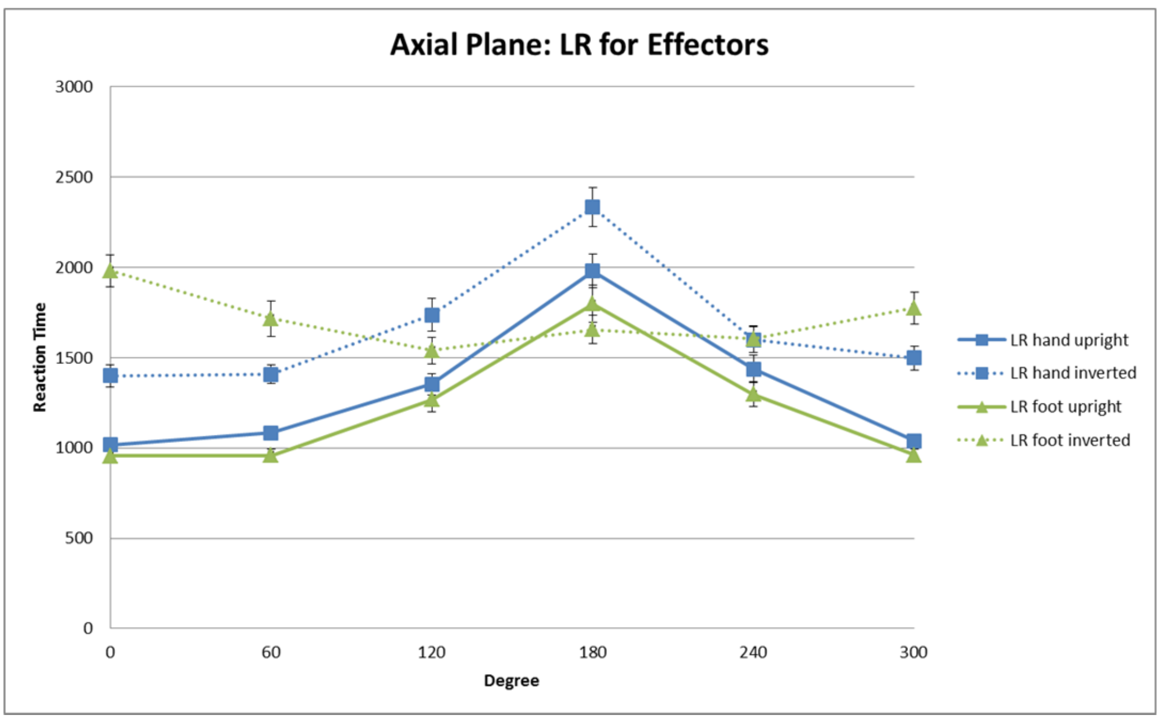

Figure 12. Reaction Time Profiles for the Left/Right Task for Effector Stimuli by Condition and View Rotated in the Axial Plane. Error bars represent -/+ 1 SEM.

Table 9

Analysis of Variance on Average RT for S/D Task with Effectors Rotated in the Axial Plane and Factor Scores as Covariates

	df	*F*	η	*p*
degree	5	3.552**	.038	.004
condition (hands, feet)	1	.082	.001	.775
view	1	16.777***	.156	< .001
degree x condition	5	.592	.006	.706
degree x view	5	2.066	.022	.069
condition x view	1	.185	.002	.668
degree x condition x view	5	1.631	.018	.150
SV	1	.974	.011	.326
SO	1	12.595**	.122	.001
KI	1	1.667	.018	.200

Note. **p* < .05. ***p* < .01. ****p* < .001.

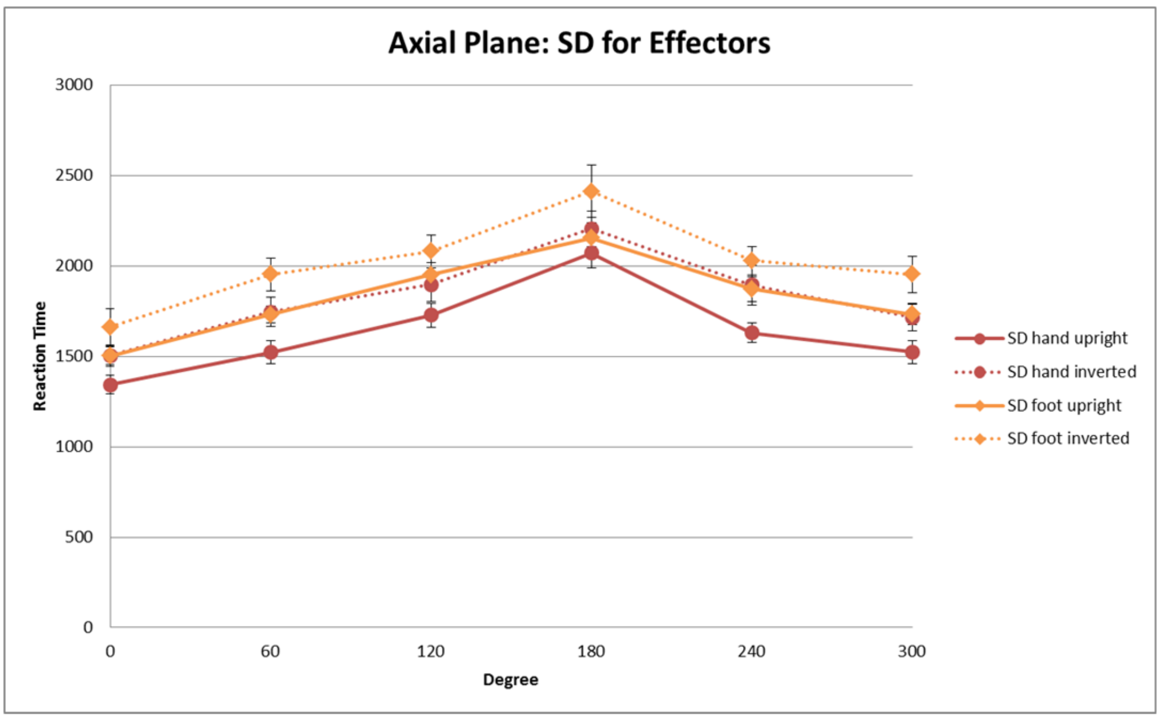

Figure 13. Reaction Time Profiles for the Same/Different Task for Effector Stimuli by Condition and View Rotated in the Axial Plane. Error bars represent -/+ 1 SEM.

each stimulus and axis of rotation combination, a 2 (task: L/R, S/D) x 6 (degree: 0, 60, 120, 180, 240, 300) x 2 (condition: arms out or across for bodies, hands or feet for body parts) x 2 (view: the front or back of bodies, top or bottom of feet) ANOVA was performed with task, degree, condition and view as within-subjects variables. In order to compare to previously published studies, only findings specific to stated hypotheses regarding differences in processes used will be discussed.[5]

Picture Plane Rotations

For bodies rotated in the picture plane (see Table 10 and Figures 6 and 7), there was a main effect of task ($F_{1,91} = 76.198$, $p < .001$; $\eta_p^2 = .448$) where S/D judgments were overall slower than L/R judgments. There was a significant task x degree interaction ($F_{5,455} = 23.095$, $p < .001$; $\eta_p^2 = .197$) suggesting a difference in RT profiles for the L/R and the S/D tasks. The chronometric profile for L/R judgments is mostly flat with a large peak at 180 degrees while the profile for S/D judgments is monotonically increasing. **For body parts** rotated in the picture plane (see Table 11 and Figures 8 and 9), there was a main effect of task ($F_{1,91} = 9.553$, $p = .003$; $\eta_p^2 = .092$) showing that S/D judgments were overall slower than L/R judgments. This was further supported by a significant interaction for task x degree ($F_{5,455} = 6.315$, $p < .001$; $\eta_p^2 = .063$).

Axial Plane Rotations

For bodies rotated in the axial plane (see Table 12 and Figures 10 and 11), there is a main effect of task ($F_{1,91} = 23.199$, $p < .001$; $\eta_p^2 = .198$) and a significant task x degree interaction ($F_{5,455} = 120.185$, $p < .001$; $\eta_p^2 = .561$). The chronometric profile for L/R judgments was mostly flat with a peak at 0 degrees where the body stimuli were

[5] All significant and nonsignificant effects can be found in Tables 10-13.

Table 10

Analysis of Variance on Average RT for Bodies Rotated in the Picture Plane

	df	*F*	η	*p*
task	1	76.198***	.448	< .001
degree	5	284.448***	.752	< .001
condition	1	65.653***	.411	< .001
view	1	85.812***	.477	< .001
task x degree	5	23.095***	.197	< .001
task x condition	1	59.883***	.389	< .001
degree x condition	5	4.900***	.050	< .001
task x degree x condition	5	9.113***	.088	< .001
task x view	1	37.460***	.285	< .001
degree x view	5	13.746***	.128	< .001
task x degree x view	5	5.134***	.052	< .001
condition x view	1	7.295**	.072	.008
task x condition x view	1	.580	.006	.448
degree x condition x view	5	.752	.008	.585
task x degree x condition x view	5	1.984	.021	.080

Note. **p* < .05. ***p* < .01. ****p* < .001.

Table 11

Analysis of Variance on Average RT for Effectors Rotated in the Picture Plane

	df	*F*	η	*p*
task	1	9.553**	.092	.003
degree	5	124.231***	.569	< .001
condition	1	19.868***	.174	< .001
view	1	203.676***	.684	< .001
task x degree	5	6.315***	.063	< .001
task x condition	1	1.140	.012	.288
degree x condition	5	.858	.009	.509
task x degree x condition	5	8.592***	.084	< .001
task x view	1	81.709***	.465	< .001
degree x view	5	10.700***	.102	< .001
task x degree x view	5	10.864***	.104	< .001
condition x view	1	25.460***	.213	< .001
task x condition x view	1	46.576***	.331	< .001
degree x condition x view	5	3.310**	.034	.006
task x degree x condition x view	5	1.635	.017	.149

Note. **p* < .05. ***p* < .01. ****p* < .001.

Table 12

Analysis of Variance on Average RT for Bodies Rotated in the Axial Plane

	df	*F*	η	*p*
task	1	23.199***	.198	< .001
degree	5	24.077***	.204	< .001
condition	1	36.134***	.278	< .001
view	1	559.242***	.856	< .001
task x degree	5	120.185***	.561	< .001
task x condition	1	26.183***	.218	< .001
degree x condition	5	3.523**	.036	.004
task x degree x condition	5	4.706***	.048	< .001
task x view	1	116.241***	.553	< .001
degree x view	5	6.190***	.062	< .001
task x degree x view	5	2.873*	.030	.014
condition x view	1	4.921*	.050	.029
task x condition x view	1	.061	.001	.805
degree x condition x view	5	.898	.009	.482
task x degree x condition x view	5	1.140	.012	.338

Note. *p < .05. **p < .01. ***p < .001.

facing toward the participant and therefore required an additional transformation to rotate the body to be in line with the participant's physical position. The chronometric profile for S/D judgments was monotonically increasing as the reference image was always the body stimulus in the 0 degree position.

For body parts rotated in the axial plane (see Table 13 and Figures 12 and 13), there a main effect of task ($F_{1,91} = 33.643$, $p < .001$; $\eta_p^2 = .264$). This main effect indicates that overall S/D judgments were slower than L/R judgments. There was a significant task x degree interaction ($F_{5,455} = 8.463$, $p < .001$; $\eta_p^2 = .083$) suggesting different RT profiles where the RT profile for S/D judgments appears slightly flatter while the RT profile for L/R judgments appears to be increasing to 180 degrees.

Table 13

Analysis of Variance on Average RT for Effectors Rotated in the Axial Plane

	df	*F*	η	*p*
task	1	33.643***	.264	< .001
degree	5	135.962***	.591	< .001
condition	1	5.358*	.054	.023
view	1	121.631***	.564	< .001
task x degree	5	8.463***	.083	< .001
task x condition	1	13.558***	.126	< .001
degree x condition	5	13.312***	.124	< .001
task x degree x condition	5	10.285***	.099	< .001
task x view	1	24.974***	.210	< .001
degree x view	5	10.638***	.102	< .001
task x degree x view	5	10.257***	.098	< .001
condition x view	1	4.235*	.043	.042
task x condition x view	1	5.048*	.051	.027
degree x condition x view	5	7.660***	.075	< .001
task x degree x condition x view	5	11.932***	.113	< .001

Note. $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

Accuracy

Accuracy scores were created for each of the 192 possible combinations. Scores were computed by adding the total number of correct trials for a given combination where the scores ranged from 0 to 4. To test whether there is evidence for differences in accuracy based on task and stimulus, an ANOVA was performed on accuracy scores. For each axis of rotation, a 2 (task: L/R, S/D) x 2 (stimuli: bodies, effectors) x 6 (degree: 0, 60, 120, 180, 240, 300) x 2 (condition: arms out or across for bodies, hands or feet for body parts) x 2 (view: the front or back of bodies, top or bottom of feet) ANOVA was performed with task, stimuli, degree, condition and view as within-subjects variables. Only findings specific to stated hypotheses will be discussed.[6]

[6] All significant and nonsignificant effects can be found in Tables 14-15.

Picture Plane Rotations

For stimuli rotated in the picture plane (see Table 14), there was a main effect of task ($F_{1,94} = 4.251$, $p = .042$; $\eta_p^2 = .043$) where participants were more accurate on the S/D task compared to the L/R task. The main effect of degree ($F_{5,470} = 51.587$, $p < .001$; $\eta_p^2 = .354$) indicates that stimuli positioned at 180° were the most difficult while stimuli positioned at 0° were the easiest. A task x stimuli interaction ($F_{1,94} = 16.813$, $p < .001$; $\eta_p^2 = .152$) shows that in the L/R task, accuracy was greater for bodies than effectors, while in the S/D task, accuracy was comparable for bodies and effectors. **For bodies**, overall accuracy was high, 94.8% with comparable accuracy seen in the S/D task (94.4%) and the L/R task (95.2%). **For effectors**, overall accuracy was not as high as for bodies, 90.8% with greater accuracy seen in the S/D task (92.6%) compared to the L/R task (89.1%). Greater difficulty with effectors suggests different processes are involved. This was further supported by a main effect of stimuli ($F_{1,94} = 76.998$, $p < .001$; $\eta_p^2 = .450$) suggesting that judgments of bodies were more accurate than judgments of effectors.

Axial Plane Rotations

For stimuli rotated in the axial plane (see Table 15), there was a main effect of task ($F_{1,94} = 9.936$, $p = .002$; $\eta_p^2 = .095$) where participants were more accurate on the S/D task compared to the L/R task. There was a main effect of degree ($F_{5,470} = 4.631$, $p < .001$; $\eta_p^2 = .046$) again indicating that stimuli positioned at 180° were the most difficult. **For bodies**, overall accuracy was high but less accurate (91.0%) than for picture plane. Participants had greater difficulty with left/right judgments (89.0%) compared to same/different judgments (93.0%). **For effectors**, overall accuracy was comparable to accuracy with bodies, 91.4% with similar accuracy seen in the same/different task

Table 14

Analysis of Variance on Average Accuracy for Stimuli Rotated in the Picture Plane

	df	*F*	η	*p*
task	1	4.251*	.043	.042
stimuli	1	76.998***	.450	< .001
degree	5	51.587***	.354	< .001
condition	1	10.914***	.104	< .001
view	1	9.553**	.092	.003
task x stimuli	1	16.813***	.152	< .001
task x degree	5	2.971*	.031	.012
stimuli x degree	5	1.347	.014	.243
task x stimuli x degree	5	2.604*	.027	.024
task x condition	1	11.416**	.108	.001
stimuli x condition	1	79.437***	.458	< .001
task x stimuli x condition	1	.320	.003	.573
degree x condition	5	5.438***	.055	< .001
task x degree x condition	5	3.305**	.034	.006
stimuli x degree x condition	5	.368	.004	.870
task x stimuli x degree x condition	5	2.211	.023	.052
task x view	1	23.282***	.199	< .001
stimuli x view	1	43.158***	.315	< .001
task x stimuli x view	1	41.264***	.305	< .001
degree x view	5	2.298*	.024	.044
task x degree x view	5	1.103	.012	.358
stimuli x degree x view	5	3.866**	.040	.002
task x stimuli x degree x view	5	3.312**	.034	.006
condition x view	1	29.842***	.241	< .001
task x condition x view	1	26.383***	.219	< .001
stimuli x condition x view	1	18.168***	.162	< .001
task x stimuli x condition x view	1	41.761***	.308	< .001
degree x condition x view	5	2.840*	.029	.015
task x degree x condition x view	5	3.500**	.036	.004
stimuli x degree x condition x view	5	1.787	.019	.114
task x stimuli x degree x condition x view	5	.484	.005	.788

Note. **p* < .05. ***p* < .01. ****p* < .001.

Table 15

Analysis of Variance on Average Accuracy for Stimuli Rotated in the Axial Plane

	df	*F*	η	*p*
task	1	9.936**	.095	.002
stimuli	1	.831	.009	.364
degree	5	4.631***	.046	< .001
condition	1	3.868	.039	.052
view	1	121.356***	.561	< .001
task x stimuli	1	10.129**	.096	.002
task x degree	5	25.518***	.212	< .001
stimuli x degree	5	14.682***	.134	< .001
task x stimuli x degree	5	14.252***	.130	< .001
task x condition	1	.898	.009	.346
stimuli x condition	1	19.322***	.169	< .001
task x stimuli x condition	1	12.64**	.117	.001
degree x condition	5	4.235**	.043	.001
task x degree x condition	5	2.300*	.024	.044
stimuli x degree x condition	5	4.710***	.047	< .001
task x stimuli x degree x condition	5	6.047***	.060	< .001
task x view	1	54.922***	.366	< .001
stimuli x view	1	31.054***	.246	< .001
task x stimuli x view	1	28.942***	.234	< .001
degree x view	5	12.593***	.117	< .001
task x degree x view	5	9.339***	.090	< .001
stimuli x degree x view	5	.612	.006	.691
task x stimuli x degree x view	5	.863	.009	.506
condition x view	1	.068	.001	.794
task x condition x view	1	2.647	.027	.107
stimuli x condition x view	1	9.67**	.092	.002
task x stimuli x condition x view	1	7.44**	.073	.008
degree x condition x view	5	2.435*	.025	.034
task x degree x condition x view	5	2.142	.022	.059
stimuli x degree x condition x view	5	4.900***	.049	< .001
task x stimuli x degree x condition x view	5	2.593*	.027	.025

Note. *$p < .05$. **$p < .01$. ***$p < .001$.

(91.8%) and the left/right task (91.0%). The comparable accuracy for bodies and effectors was reinforced by no significant effect of stimuli ($F_{1,94}$ = .831, p = .364; η_p^2 = .009). There was a significant interaction of task x stimuli ($F_{1,94}$ = 10.129, p = .002; η_p^2 = .096) where judgments of effectors were more accurate for the L/R task but less accurate for the S/D task.

Overall difficulties with stimuli rotated in the axial plane suggest that axial plane rotations are different from picture rotations based on the presented stimuli. For picture plane rotations, the whole body is visible at all times (see Appendix A). All of the fingers on the hand and the toes on the feet are always visible (see Appendix B). For axial plane rotations, parts of the body and of the effectors become occluded as it is rotated (see Appendix A). While occlusion was purposefully minimized for the stimuli, the inherent nature of axial rotations necessitates that the parts of the stimuli will be obstructed to a certain extent, adding to the difficulty of these judgments.

Discussion

The use of spatial transformations is ubiquitous in everyday cognitive processing from reading maps to planning actions to reasoning. Typically, spatial transformations have been defined in relation to the spatial reference frame (i.e., an egocentric-centered, an object-centered, or an environmental reference frame) that is updated. A particular focus in the literature has been on object-based and perspective-based transformations that update object-centered and egocentric-centered reference frames respectively to each other and to the environmental reference frame (e.g., Hegarty & Waller, 2004; Presson, 1982; Wraga, et al., 1999; Wraga, Creem, & Proffitt, 2000; Zacks, Mires, et al., 2002; Zacks & Tversky, 2005). Primarily these two spatial transformations were singled out for their crucial role in spatial reasoning. However growing research work has classified a third spatial transformation, effector-based transformations that are characterized as the updating of a body part centered egocentric reference frame (Creem-Regehr, et al., 2007; Parsons, 1987b; Zacks & Michelon, 2005) as opposed to a head-centered or eye-centered egocentric reference frame (Colby, 1998) as is the case with perspective-based transformations. Another difference with effector-based transformations is the recruitment of motor simulation mechanisms. Neuroimaging data indicates that unique motor processes are recruited in effector-based transformations but not in object-based or perspective-based transformations (Bonda, Petrides, Frey, & Evans, 1995; Creem-Regehr, et al., 2007; Vingerhoets, et al., 2002).

The first goal of this thesis was to understand how different spatial transformations may recruit similar or different processes and how these processes are influenced by spatial ability. Previously, object-based and perspective-based transformations have been studied behaviorally using a same/different task and a left/right task respectively that consistently elicit unique response time profiles as a function of stimulus orientation (e.g., Parsons, 1987a; Zacks, Mires, et al., 2002; Zacks, Ollinger, et al., 2002). In these studies, spatial transformations were tested using whole body stimuli, where a change in task demands (i.e., left/right judgment vs. same/different judgment) differentially recruited spatial transformations. In the same/different task, bodies appear to be treated as objects, showing an increasing RT function up to 180 degrees whereas the left/right task appears to recruit an egocentric strategy to decide about an outstretched arm, showing little or no effect of degree. Effector-based transformations have been studied predominantly using hand stimuli in these same tasks

(Bonda, et al., 1995; de Lange, Helmich, & Toni, 2006; Kosslyn, et al., 1998; Parsons, 1994; Parsons, et al., 1995; Sekiyama, 1982; Vingerhoets, et al., 2002), but a distinction has not been seen between left/right and same/different tasks with effectors. These studies have shown that participant responses reflect the biomechanical constraints of natural left and right hand movement suggesting that participants mentally rotate their own hands to coincide with the stimulus orientation and then make a comparison. Effector-based transformations are constrained by the physical properties of rotation (e.g., Creem-Regehr, et al., 2007; de Lange, et al., 2006; Parsons, 1987b; Petit, Pegna, Mayer, & Hauert, 2003; Sekiyama, 1982). Behavioral performance suggest that participants mentally simulate body part movement instead of engaging in visual mental rotation where the posture of the effector stimulus (e.g., palm facing or away) and the direction of rotation affects performance (e.g., Kosslyn, et al., 1998; Parsons, et al., 1995; Vingerhoets, et al., 2002). These previous findings may explain the chronometric profiles we found in this study. Because trials for the left/right task are averaged across degree by condition and view, we lose the information for the laterality of the stimuli. It is possible that slowed RT for unnatural rotations of effectors (e.g., rotating a right hand clockwise) and speeded RT for natural rotations of effectors (e.g., rotating a right hand counterclockwise) are resulting in averaged increased RT at 120 and 240 degrees. However if the data were broken down to distinguish the laterality of the effector stimuli, there would only be two trials per 384 stimulus combinations reducing effect size.

The relationship of spatial ability and spatial transformation processes is more complicated than hypothesized. Previous research has focused on object- and perspective-based transformations and how they relate to the spatial ability factors of spatial visualization and spatial orientation (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001). Given previous behavioral and neuroimaging research suggesting the role of motor simulation in spatial transformations, we tested the relationship of spatial transformations and the spatial abilities of spatial orientation, spatial visualization, and kinesthetic imagery. First, this was done with a confirmatory factor analysis to test the suggested factor structure of the psychometric tests. The values of fit indices suggest that the three-factor model has acceptable fit for the observed data. While the three-factor model indicates that spatial orientation and spatial visualization are highly correlated consistent with previous studies, kinesthetic imagery was not correlated with either spatial orientation or spatial visualization, as expected.

In this first study, the resulting factor scores from the CFA were then used to test predictions based on the processes recruited for different tasks and stimuli (see Table 16). Of particular interest is whether spatial orientation, spatial visualization, or kinesthetic

Table 16

Spatial Ability as Predictor of Spatial Transformation Performance

Task	Picture Plane	Axial Plane
L/R		
Bodies	KI	–
Effectors	KI	SO
S/D		
Bodies	SV	SV
Effectors	SO	SO

Note. SV = spatial visualization. SO = spatial orientation. KI = kinesthetic imagery.

imagery ability predicts performance on effector-based transformations for a given task. Previous studies have suggested that effector-based transformations involve kinesthetic mechanisms (e.g., Sekiyama, 1982; Vingerhoets, et al., 2002). Our data suggest that motor imagery is required for effector-based transformations in L/R judgments of body parts but also for perspective-based transformations in L/R judgments of whole bodies. For stimuli rotated in the picture plane, performance on the left/right task with body stimuli was predicted by KI contrary to previous work linking SO and left/right judgments of bodies. Three-dimensional models of bodies and body parts were used possibly influencing responses where the 3D stimuli were more embodied compared to the 2D line drawings used in previous studies. It is also possible that a relationship with KI would have been found previously had it been evaluated in earlier research. Performance on left/right task with effector stimuli was predicted by KI consistent with our hypothesis that left/right judgments of body parts require KI. Performance on the same/different task with body stimuli was predicted by SV as hypothesized. Others have argued that in the same/different task bodies are treated as objects and therefore require an object-based transformation (e.g., Steggemann, et al., 2011; Zacks, Mires, et al., 2002). Performance on the same/different task with body part stimuli was predicted by SO and not KI as hypothesized or by SV if effectors were treated as objects. The influence of SO suggests that effectors are more embodied in the S/D task. Some participants described a strategy where they compared the reference image and the target image to see if they made a “pair” (e.g., one left hand and one right hand) and then responded “different” otherwise they responded “same.” This strategy is possibly different from a mental rotation strategy of rotating the target image to the same orientation of the reference image. Determining what constitutes a pair is a strategy that would only be efficient for effectors and not bodies. The differences in the influence of spatial ability factors across these four conditions (L/R bodies, L/R effectors, S/D bodies, S/D effectors) suggest that different transformations underlie performance on these tasks.

For stimuli rotated in the axial plane, there was no influence of SO, or any spatial ability, on performance on left/right judgments of bodies. For left/right judgments of body parts, SO predicted performance and not KI, in contrast to the same task performed in the picture plane. This may be due to the stimuli being presented in a way that was consistent with the participant's physical position (i.e., the hands and feet extended in depth away from the participant, aligned with their natural orientation, see Appendix B). Participants commented on using a strategy where they imagined themselves in the position of the feet or hands. For same/different judgments of bodies, SV predicted performance as expected. For body parts, same/different judgments were predicted by SO consistent with effectors rotated in the picture plane.

RT performance across bodies and effectors was also evaluated for each task to test whether there is evidence for similar or different chronometric profiles. Similarities or differences in the chronometric profiles would infer similar or different underlying spatial transformation mechanisms. Differences as a function of stimuli type (bodies, effectors), condition (arm across/out, hand/foot), and view (front/back, upright/inverted) were also assessed as evidence of varying mechanisms.

For bodies rotated in the picture plane, the chronometric profile (see Figure 7) for the same/different task with body stimuli is a monotonically increasing function while the chronometric profile for the left/right task with body stimuli is a mostly flat function with a peak at 180^{o} consistent with Creem-Regehr, et al. (2007) where the increase in reaction time is probably due to a left/right conflict rather than due to a spatial transformation. The typical chronometric profiles for bodies are indicated by no effect of degree seen in the left/right task and a main effect of degree seen in the same/different task. The task x degree interaction (see Figure 7) further supports that the left/right and same/different tasks with body stimuli are eliciting chronometric profiles consistent with previous studies (e.g., Parsons, 1987a, 1987b), suggesting that the left/right task involves perspective-based transformations and the same/different task involves object-based transformations.

For effectors rotated in the picture plane, there were similar findings to bodies but a difference in RT profiles (see Figures 8 and 9). The chronometric profile for left/right task is consistent with early mental rotation studies done with hand stimuli rotated in the picture plane (Ashton, McFarland, Walsh, & White, 1978; Cooper & Shepard, 1975). The degree x condition x view interaction (see Figures 8 and 9) illustrates that task performance for body part stimuli is differentially affected by the bottoms of hands and feet. Bottoms of effectors take longer to transform than tops perhaps because an additional transformation is required to mentally rotate the effector to be consistent with our normal physical experience with effectors (i.e., viewing the tops of effectors). Furthermore, bottoms of feet are the most difficult to transform again suggesting an effect of less experience interacting with feet bottoms. This may indicate that body parts are being solved with more of a perspective-based transformation than an object-based transformation consistent with the finding that SO predicts performance for S/D judgments of effectors.

Previous research has explored spatial transformations in different planes of rotation (Carpenter & Proffitt, 2001; Creem, Wraga, & Proffitt, 2001; Parsons, 1987a, 1987b; Zacks & Michelon, 2005) and found that participants had difficulty with rotations in specific axes. For stimuli rotated in the axial plane (see Figures 10-13), the chronometric profiles for left/right and same/different judgments are not the same as the profiles in the picture plane. The main effect of degree for the left/right task for bodies seems to be driven by a significant difference in mean RT for responding to bodies positioned at 0 degrees compared 60 degrees ($F_{1,91} = 12.5$, $p = .001$; $\eta_p^2 = .122$). Because the 0 position for bodies is facing the participant, this may be due to either a left/right conflict rather than difficulty with spatial transformation or the need for an additional transformation in order for the body to be in line with the participants physical position. There is a main effect of degree for left/right task for effectors that seems to be driven by a significant difference in mean RT for effectors positioned at 240 compared to 300 degrees ($F_{1,91} = 8.812$, $p = .004$; $\eta_p^2 = .088$), which is consistent with difficulty making judgments of body parts that are in a biomechanically impossible position. Research has shown that L/R judgments of inverted whole bodies illicit slower reaction times compared to upright bodies (Zacks, Hazeltine, et al., 1999). Surprisingly there is no effect of view (i.e., upright vs. inverted) for left/right judgments of bodies (see Figure 10). Although there appears to be an effect of view for L/R judgments for both the 180 degree rotations of bodies in the picture plane and inverted bodies rotated in the axial plane, the KI covariate is masking the effect. There is however an effect of view for left/right judgments of body parts. This finding in combination with significant interactions for degree x condition and degree x view suggest greater difficulty judging feet compared to hands and upside-down body parts compared to right side up (see Figure 11). This may be because of less experience with seeing our feet in different positions from how we experience them as connected to our bodies and with seeing our effectors in inverted positions. There was a main effect of degree and view on performance in the same/different task for bodies and for body parts indicating that reaction time increased as degree disparity increased to 180 degrees and that judgments on inverted stimuli took longer than upright stimuli.

Overall, we found that the same/different and left/right tasks for bodies and effectors require different spatial ability factors and elicit different spatial transformations based on varying chronometric profiles given the same participants, stimuli and task parameters. This suggests that three distinct processes are involved in solving these tasks. In summary, in addition to finding further support for the relationship of spatial visualization ability to object-based transformations of bodies, we provide novel insights into the role of kinesthetic imagery and spatial orientation ability on transformations of bodies and body-parts. Specifically, the kinesthetic imagery factor predicted performance on left/right decisions of body-parts, as expected, but also left/right decisions of bodies. While the effect of kinesthetic imagery on perspective-based transformations of bodies has not been found (or looked for) before, it is not totally surprising, given the possibility of solving the decision of an outstretched arm with motor simulation. We did not find support for the influence of spatial orientation ability on left/right decisions of bodies, as shown in previous work. One possibility is that in the present analysis, KI accounted for any SO effect that was present. Another possibility is that the realism and 3D nature of the stimuli elicited more of a motor simulation than an egocentric strategy. Finally, the effects of spatial orientation ability on decisions about body-parts in the axial plane are also interesting to consider, as axial plane rotations with hands have not been explored much in the literature. As suggested by some subjective reports, participants may have solved the task by rotating their own perspective into the stimulus orientation, which would be consistent with a spatial orientation/egocentric transformation process.

Acknowledgments

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STUDY 2

Abstract

Behavioral and neuroimaging research support the idea that different types of spatial transformations (object-based, perspective-based, and effector-based) utilize distinct processing resources and the efficiency by which these resources are used can differ by individual. It is known that there are differences in performance on spatial tasks as a function of general spatial ability, such as superior performance in object mental rotation for high versus low spatial ability. However, the contribution of spatial expertise to the processing of spatial transformations is unexplored. Spatial experts, or individuals who score high on traditional measures of spatial ability and whose expertise relies on the utilization of specific reference frames, are predicted to show maximum efficiency on a specific type of transformation related to their expertise (Steggemann, et al., 2011). Modern dancers should show better performance on effector-based transformations based on their training and practice in Laban's spatial awareness or body awareness (Laban, 1950; Leman & Naveda, 2010). Formally trained dancers were used to test our hypotheses. All participants completed psychometric tests of the three spatial ability factors as well as performed computer-based spatial transformation tasks that measured reaction time and accuracy. Dancers were compared to nondancer controls and were found to significantly differ in kinesthetic imagery. Behavioral differences on computer-based tasks were evaluated as a function of expertise group. Dancer performance on the

transformation tasks suggested more dynamic versus static processing of stimuli than controls.

Introduction

The use of spatial transformations is intrinsic to our everyday life and a major component to spatial thinking. Spatial thinking is central to everyday reasoning, representation, communication, and navigation. This was emphasized by a recent National Research Council (Downs & DeSouza, 2006) recommendation to integrate spatial thinking in all courses in K-12 curriculums. However, a lack of translational studies has led the National Research Council to challenge researchers to investigate the generalizability of spatial thinking interventions. This highlights the importance of understanding how spatial thinking can be improved through structured practice and direct experience (Ericsson, et al., 1993; Sloboda, Davidson, Howe, & Moore, 1996). One approach to determining teaching and training interventions is to identify spatial experts who excel in desirable abilities or component processes and use their training as a model. Chi (2006) referred to this approach as the relative approach, where expertise is considered to be a level of proficiency that is achievable by novices. This is in contrast to the absolute approach, where expertise is primarily attributed to inherited or innate characteristics. The relative approach assumes that experts have gained structured and organized knowledge within a domain (Ericsson & Smith, 1991), have domain general abilities that are similar to novices, and have differentially represented knowledge (Bédard & Chi, 1992; Chi, 2006; Clark, 2008). For example, the use of specific reference frames is inherent in many professions, such as science and dance, leading to extensive focused training that those outside of the discipline likely do not gain (Ericsson &

Charness, 1994; Jola & Mast, 2005; Keehner, Lippa, Montello, Tendick, & Hegarty, 2006; Klatzky & Wu, 2008). Expertise using a specific reference frame has implications as to the perceptual and cognitive processing involved in making spatial judgments and performing actions (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005; Haueisen & Knösche, 2001; Tarampi, Geuss, Stefanucci, & Creem-Regehr, 2010).

The aim of this study was to use spatial expertise to test the relationship among three types of spatial transformations – object-, perspective-, or effector-based transformations. Spatial experts will be used to assess the relationship between effector-based transformations and the other transformations as it relates to their expertise in order to evaluate the extent to which processes are shared among the transformations or if different processes are utilized by experts. Their performance will be evaluated on six psychometric tests of spatial ability and four computer-based spatial transformation tasks.

To compare with the existing literature, formally trained dancers will be used to test our hypotheses. Dancers and nondancer controls will be compared on psychometric tests of the three spatial ability factors to see if dancers differ from controls in kinesthetic imagery ability (KI) based on their training and practice in codified dance and Laban's spatial awareness (Laban, 1950; Leman & Naveda, 2010). Behavioral differences on computer-based reaction time spatial transformation tasks will also be evaluated as a function of expertise group. If dancers are high in kinesthetic imagery ability then we would expect dancers to have an advantage on tasks and stimuli requiring KI.

Method

Participants

A total of 112 young adults participated from the University of Utah psychology undergraduate participant pool. These are the same participants from study 1. The same exclusion criteria were used resulting in 95 nondancers (37 males, 58 females, mean age = 21.42 years) who were included in the analyses. An additional 23 dancers (4 males, 19 females, mean age 25.52 years) were recruited from the University of Utah psychology undergraduate participant pool, the University of Utah Department of Modern Dance, or the greater Salt Lake community. The inclusion criteria for the expert group were that the individual had at least 10 years of formal dance training and was currently practicing on a regular basis (at least weekly if not daily). Each participant completed a battery of psychometric tests and computer-based tasks during a testing session that lasted approximately two hours. Participants were compensated with credit towards a psychology course requirement, or ten dollars per hour. All participants had normal or corrected-to-normal vision.

Materials

The same materials were used as in Study 1. In summary, the materials consisted of six psychometric tests of spatial ability and four computer-based spatial transformation tasks. Spatial orientation ability was measured with the Perspective Taking/Spatial Orientation Test (SOT; Hegarty & Waller, 2004) and Money's Road-Map Test of Direction Sense (Money, et al., 1965). Spatial visualization ability was measured with the Paper Folding Test (PFT; Ekstrom, et al., 1976) and the Cube Comparison Test (CCT; Ekstrom, et al., 1976). Kinesthetic imagery ability was measured with the Movement

Imagery Questionnaire Revised Second Version (MIQ-RS; Gregg, et al., 2007) and the Vividness of Movement Imagery Questionnaire (VMIQ-2; Roberts, et al., 2008).

Computer-based Design

The same design for the computer-based tasks was used as in Study 1 with the addition of expertise group (nondancers or dancers) considered as a between subject variable. In summary, a 2 (group) x 2 (stimuli) x 2 (task) x 2 (axis) x 6 (degree) x 2 (condition) x 2 (view) factorial design in which stimuli (bodies or body parts), task (same/different or left/right), axis (picture plane or axial plane), degree (0, 60, 120, 180, 240, and 300 degrees), condition (bodies with arms outstretched or arms across their body; hands or feet) and view (front or back of stimuli; right-side up or upside-down) were within-subjects variables, and group (nondancers or dancers) was a between-subjects variable. All stimuli and tasks were the same as in Experiment 1.

Procedure

The same procedure was used to test the additional dancer participants.

Results

Coding

The raw data from E-Prime for the computer-based tasks was compiled as in Study 1. The spatial abilities tests were coded and scored as in Study 1.

Analyses

Independent-samples t-tests were conducted to compare psychometric test scores between dancers and nondancer controls. Missing RT data cells for controls were replaced with the sample average for that cell. .71% of cells were replaced. Missing data cells for dancers were replaced with the sample average for that cell. .18% of cells were replaced.

Results

Independent-Samples *T*-tests

Dancers' scores on the visual (M = 44.3043, SD = 5.56315) and kinesthetic (M = 44.0435, SD = 5.47289) sections of the MIQ-RS revealed significant differences compared to controls (visual M = 40.1263, SD = 5.98267; kinesthetic M = 38.9789, SD = 7.15182), $t(116) = -3.044$, $p = 0.003$; $t(116) = -3.175$, $p = 0.002$, respectively). On the kinesthetic section of the VMIQ-2, dancers (M = 18.4783, SD = 7.32908) scored significantly better than controls (M = 24.5366, SD = 8.34216) where a lower score means higher kinesthetic imagery ability. There were no other differences between dancers and controls (see Table 17).

ANOVA

For each stimulus and axis of rotation combination, separate 2 (group: control, dancer) x 2 (task: L/R, S/D) x 6 (degree: 0, 60, 120, 180, 240, 300) x 2 (condition: arms out or across for bodies, hands or feet for body parts) x 2 (view: the front or back of bodies, top or bottom of feet) ANOVAs were performed on mean RT with task, degree,

Table 17

Mean and Standard Deviation for Psychometric Tests According to Group

Variable	n	M	SD	*t*	*p*
PFT					
Controls	95	9.658	4.999	-.502	.617
Dancers	23	10.228	4.408		
CCT					
Controls	95	18.590	9.879	-.365	.716
Dancers	23	19.435	10.290		
SOT					
Controls	95	36.289	30.850	-.470	.639
Dancers	23	40.043	46.579		
MRM					
Controls	95	30.305	2.682	-.727	.469
Dancers	23	30.739	2.005		
MIQ-RS VIS					
Controls	95	40.126	5.983	-3.044**	.003
Dancers	23	44.304	5.563		
MIQ-RS KIN					
Controls	95	38.979	7.152	-3.175**	.002
Dancers	23	44.044	5.473		
VMIQ-2 IVI					
Controls	95	22.263	8.113	.351	.726
Dancers	23	21.609	7.632		
VMIQ-2 EVI					
Controls	95	28.747	9.205	.731	.466
Dancers	23	27.087	11.912		
VMIQ-2 KIN					
Controls	95	24.537	8.342	3.195**	.002
Dancers	23	18.478	7.329		

Note. *M* = mean. *SD* = standard deviation. *$p < .05$. **$p < .01$. ***$p < .001$.

condition and view as within-subjects variables and group as a between-subjects variable. Only findings specific to stated hypotheses will be discussed.[7]

Picture Plane Rotations

For bodies (see Table 18 and Figure 14), there is a significant degree x group interaction ($F_{5,580} = 3.549$, $p = .004$; $\eta_p^2 = .030$) showing that dancers are slower across all degree disparities than controls with dancers having greatest difficulty with stimuli presented between 120-240 degrees . This was supported by a significant difference between bodies positioned at 120 degrees and 180 degrees ($F_{1,116} = 6.391$, $p = .013$; $\eta_p^2 = .052$), and between bodies positioned at 180 degrees and 240 degrees ($F_{1,116} = 6.258$, $p = .014$; $\eta_p^2 = .051$). **For body parts** (see Figure 15 and Table 19), there is a main effect of group ($F_{1,116} = 4.345$, $p = .039$; $\eta_p^2 = .036$) indicating that dancers are overall slower in RT compared to controls. There is a task x group interaction ($F_{1,116} = 5.537$, $p = .020$; $\eta_p^2 = .046$), where dancers are slower on the L/R judgments but not different than controls on S/D judgments compared to controls. There is a view x group interaction ($F_{1,116} = 6.380$, $p = .013$; $\eta_p^2 = .052$), showing that controls are faster than dancers to respond to the bottoms of effectors but there is no difference for the tops of effectors. There is a task x view x group interaction ($F_{1,116} = 11.216$, $p = .001$; $\eta_p^2 = .088$) revealing that compared to controls, dancers are overall slower in the L/R task for both tops and bottoms of effectors but comparable in performance to controls for the S/D task.

[7] All significant and nonsignificant effects can be found in Tables 18-21.

Table 18

Analysis of Variance on Average RT for Bodies Rotated in the Picture Plane and Factor Scores as Covariates

	df	*F*	η	*p*
task	1	45.157***	.280	< .001
task x group	1	.725	.006	.396
degree	5	254.594***	.687	< .001
degree x group	5	3.549**	.030	.004
condition	1	62.589***	.350	< .001
condition x group	1	.311	.003	.578
view	1	80.978***	.411	< .001
view x group	1	1.840	.016	.178
task x degree	5	13.760***	.106	< .001
task x degree x group	5	.297	.003	.915
task x condition	1	57.085***	.330	< .001
task x condition x group	1	1.146	.010	.287
degree x condition	5	8.342***	.067	< .001
degree x condition x group	5	1.375	.012	.232
task x degree x condition	5	6.539***	.053	< .001
task x degree x condition x group	5	1.053	.009	.385
task x view	1	50.721***	.304	< .001
task x view x group	1	3.724	.031	.056
degree x view	5	16.132***	.122	< .001
degree x view x group	5	.985	.008	.426
task x degree x view	5	6.780***	.055	< .001
task x degree x view x group	5	2.973*	.025	.012
condition x view	1	1.738	.015	.190
condition x view x group	1	1.305	.011	.256
task x condition x view	1	1.974	.017	.163
task x condition x view x group	1	.530	.005	.468
degree x condition x view	5	1.274	.011	.273
degree x condition x view x group	5	.861	.007	.507
task x degree x condition x view	5	1.252	.011	.283
task x degree x condition x view x group	5	1.541	.013	.175
group	1	2.026	.017	.157

Note. *$p < .05$. **$p < .01$. ***$p < .001$.

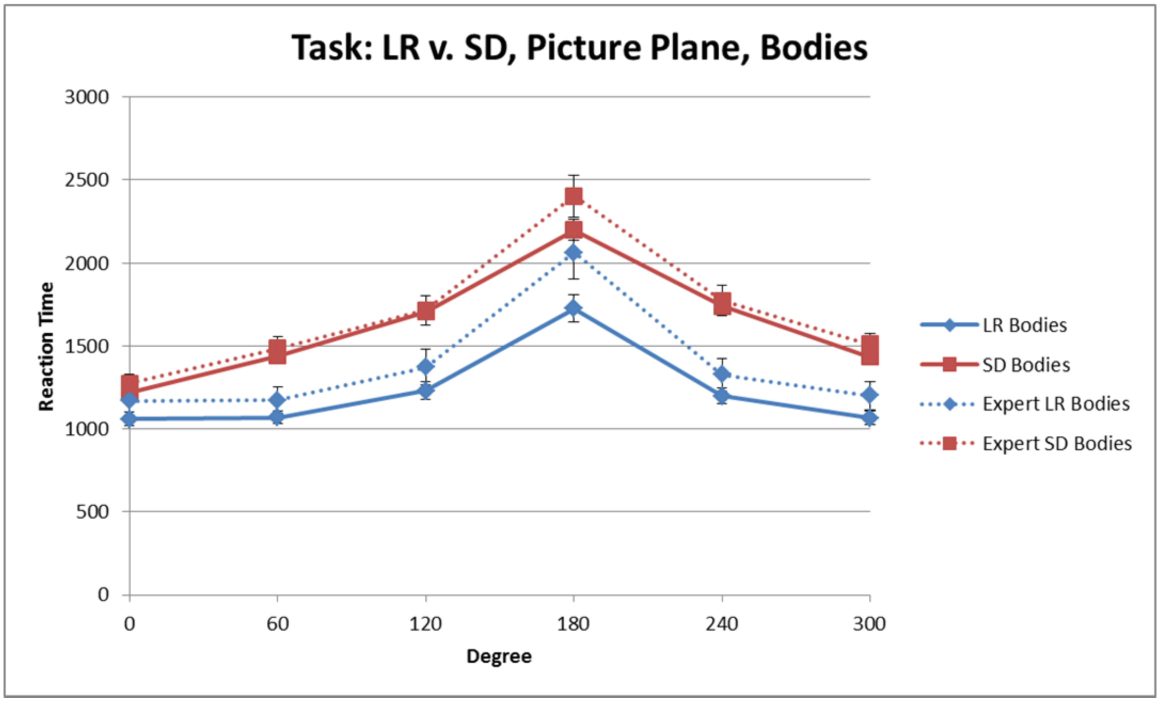

Figure 14. Reaction Time Profiles of Controls versus Dancers for the Left/Right and Same/Different Task for Body Stimuli Rotated in the Picture Plane.
Error bars represent -/+ 1 SEM.

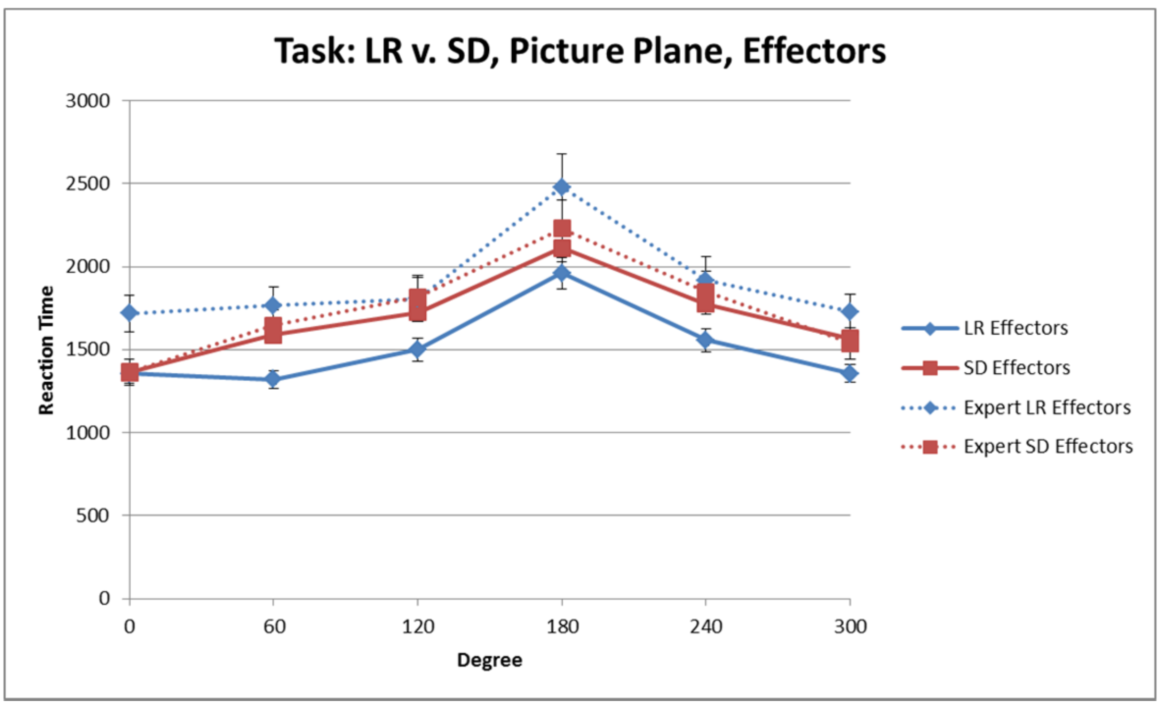

Figure 15. Reaction Time Profiles of Controls versus Dancers for the Left/Right and Same/Different Task for Effector Stimuli Rotated in the Picture Plane.
Error bars represent -/+ 1 SEM.

Table 19

Analysis of Variance on Average RT for Effectors Rotated in the Picture Plane and Factor Scores as Covariates

	df	*F*	η	*p*
task	1	.014	< .001	.906
task x group	1	5.537*	.046	.020
degree	5	102.986***	.470	< .001
degree x group	5	1.065	.009	.379
condition	1	26.968***	.189	< .001
condition x group	1	1.526	.013	.219
view	1	210.205***	.644	< .001
view x group	1	6.380*	.052	.013
task x degree	5	6.302***	.052	< .001
task x degree x group	5	.809	.007	.543
task x condition	1	.286	.002	.594
task x condition x group	1	2.058	.017	.154
degree x condition	5	1.637	.014	.148
degree x condition x group	5	1.347	.011	.243
task x degree x condition	5	10.179***	.081	< .001
task x degree x condition x group	5	.868	.007	.502
task x view	1	114.253***	.496	< .001
task x view x group	1	11.216**	.088	.001
degree x view	5	8.883***	.071	< .001
degree x view x group	5	1.066	.009	.378
task x degree x view	5	10.142***	.080	< .001
task x degree x view x group	5	1.308	.011	.259
condition x view	1	19.542***	.144	< .001
condition x view x group	1	.001	< .001	.970
task x condition x view	1	24.083***	.172	< .001
task x condition x view x group	1	.396	.003	.531
degree x condition x view	5	1.041	.009	.393
degree x condition x view x group	5	1.069	.009	.376
task x degree x condition x view	5	1.133	.010	.341
task x degree x condition x view x group	5	.566	.005	.726
group	1	4.345*	.036	.039

Note. *$p < .05$. **$p < .01$. ***$p < .001$.

Axial Plane Rotations

For bodies (see Table 20 and Figure 16), there are no significant interactions with group. **For body parts** (see Figure 17 and Table 21), there was a significant task x group interaction ($F_{1,116} = 4.927$, $p = .028$; $\eta_p^2 = .041$), where controls had faster RT than dancers for the L/R task but comparable performance for the S/D task. There is a significant interaction of task x degree x group ($F_{5,580} = 2.772$, $p = .017$; $\eta_p^2 = .023$) showing that controls are faster across all degrees for L/R judgments but slower across all degrees for S/D judgments. There is also a significant task x view x group interaction ($F_{1,116} = 9.722$, $p = .002$; $\eta_p^2 = .077$) where dancers are slower than controls for L/R judgments of both tops and bottoms of effectors and faster for S/D judgments of both tops and bottoms of effectors.

Accuracy

Accuracy scores were created for each of the 192 possible combinations. Scores were computed by adding the total number of correct trials for a given combination where the scores ranged from 0 to 4. To test whether there is evidence for differences in accuracy based on task and stimulus, an ANOVA was performed on accuracy scores. For each axis of rotation, a 2 (group: control, dancer) x 2 (task: L/R, S/D) x 2 (stimuli: bodies, effectors) x 6 (degree: 0, 60, 120, 180, 240, 300) x 2 (condition: arms out or across for bodies, hands or feet for body parts) x 2 (view: the front or back of bodies, top or bottom of feet) ANOVA was performed with task, stimuli, degree, condition and view as within-subjects variables and group as a between-subjects variable. Only findings specific to stated hypotheses will be discussed.[8]

[8] All significant and nonsignificant effects can be found in Tables 22-23.

Table 20

Analysis of Variance on Average RT for Bodies Rotated in the Axial Plane and Factor Scores as Covariates

	df	*F*	η	*p*
task	1	11.208**	.088	.001
task x group	1	.820	.007	.367
degree	5	25.044***	.178	< .001
degree x group	5	1.167	.010	.324
condition	1	34.805***	.231	< .001
condition x group	1	.258	.002	.613
view	1	523.678***	.819	< .001
view x group	1	2.337	.020	.129
task x degree	5	92.764***	.444	< .001
task x degree x group	5	.577	.005	.718
task x condition	1	24.855***	.176	< .001
task x condition x group	1	.092	.001	.762
degree x condition	5	3.139**	.026	.008
degree x condition x group	5	.439	.004	.821
task x degree x condition	5	8.691***	.070	< .001
task x degree x condition x group	5	2.046	.017	.071
task x view	1	98.812***	.460	< .001
task x view x group	1	1.116	.010	.293
degree x view	5	6.026***	.049	< .001
degree x view x group	5	1.273	.011	.274
task x degree x view	5	3.717**	.031	.003
task x degree x view x group	5	.785	.007	.560
condition x view	1	1.414	.012	.237
condition x view x group	1	.589	.005	.444
task x condition x view	1	.009	< .001	.927
task x condition x view x group	1	.015	< .001	.902
degree x condition x view	5	.593	.005	.705
degree x condition x view x group	5	.528	.005	.755
task x degree x condition x view	5	1.094	.009	.363
task x degree x condition x view x group	5	1.125	.010	.346
group	1	.325	.003	.570

Note. *$p < .05$. **$p < .01$. ***$p < .001$.

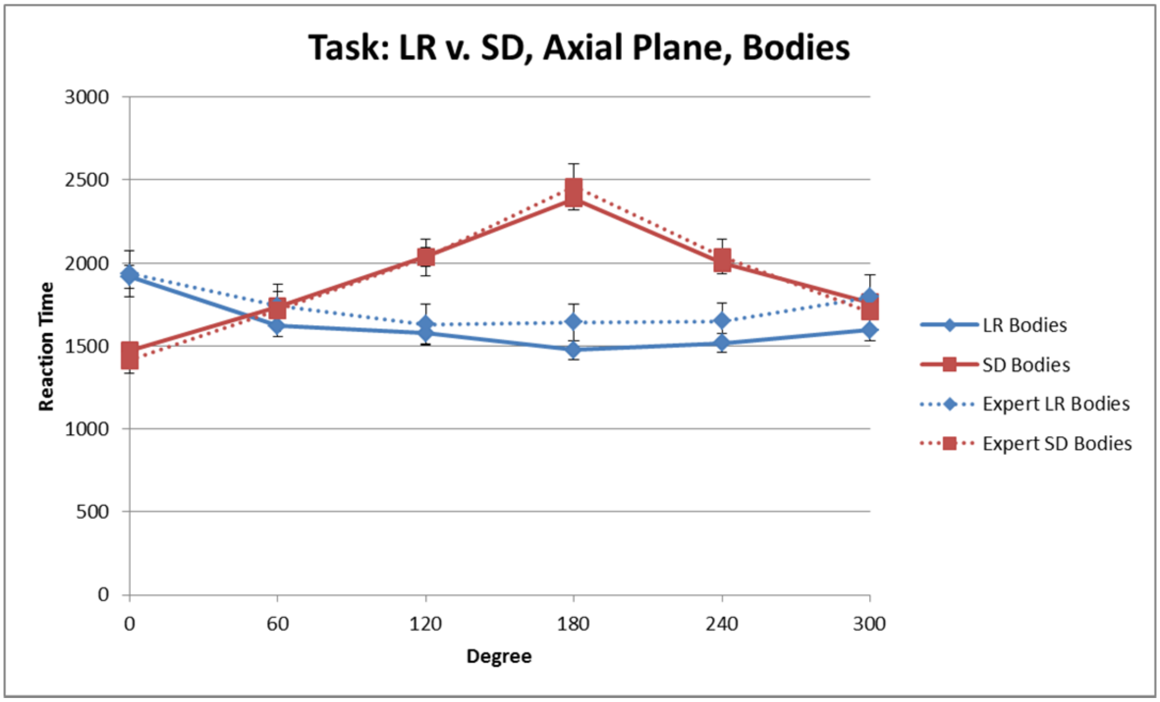

Figure 16. Reaction Time Profiles of Controls versus Dancers for the Left/Right and Same/Different Task for Body Stimuli Rotated in the Axial Plane.
Error bars represent -/+ 1 SEM.

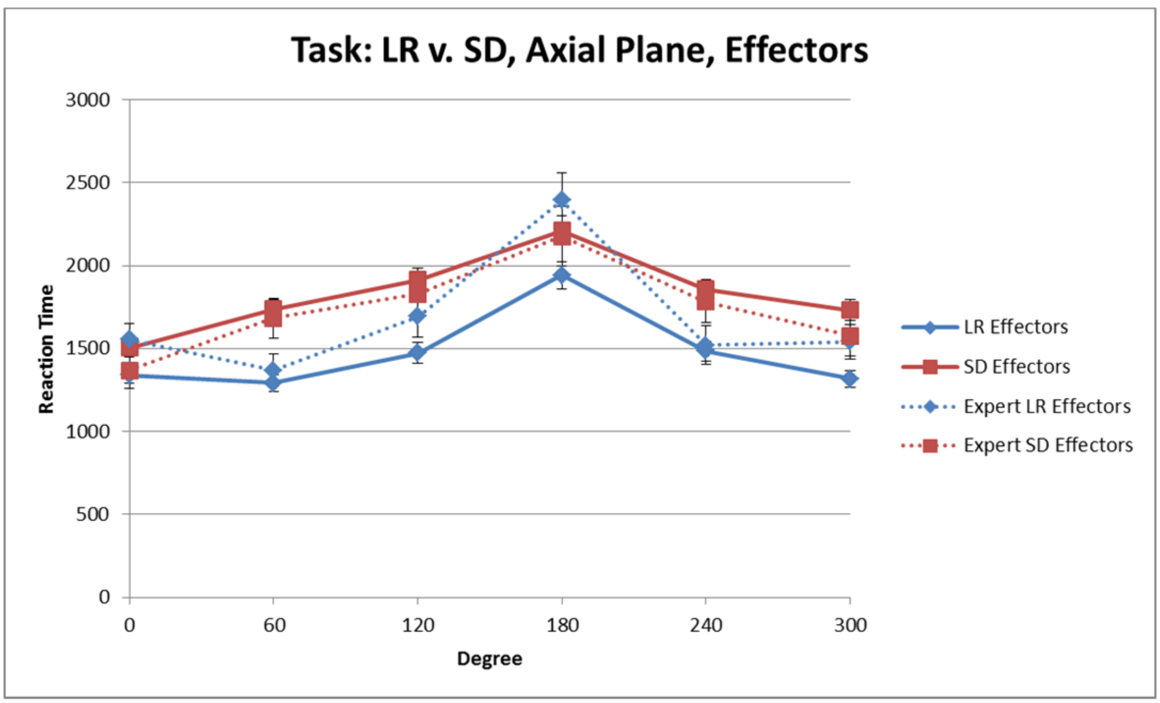

Figure 17. Reaction Time Profiles of Controls versus Dancers for the Left/Right and Same/Different Task for Effector Stimuli Rotated in the Axial Plane.
Error bars represent -/+ 1 SEM.

Table 21

Analysis of Variance on Average RT for Effectors Rotated in the Axial Plane and Factor Scores as Covariates

	df	*F*	η	*p*
task	1	9.481**	.076	.003
task x group	1	4.927*	.041	.028
degree	5	129.296***	.527	< .001
degree x group	5	2.906*	.024	.013
condition	1	13.225***	.102	< .001
condition x group	1	2.269	.019	.135
view	1	113.768***	.495	< .001
view x group	1	1.621	.014	.206
task x degree	5	13.283***	.103	< .001
task x degree x group	5	2.772*	.023	.017
task x condition	1	7.374**	.060	.008
task x condition x group	1	.227	.002	.634
degree x condition	5	15.186***	.116	< .001
degree x condition x group	5	1.424	.012	.214
task x degree x condition	5	16.006***	.121	< .001
task x degree x condition x group	5	1.902	.016	.092
task x view	1	54.545***	.320	< .001
task x view x group	1	9.722**	.077	.002
degree x view	5	5.005***	.041	< .001
degree x view x group	5	1.359	.012	.238
task x degree x view	5	14.253***	.109	< .001
task x degree x view x group	5	.993	.008	.421
condition x view	1	11.939**	.093	.001
condition x view x group	1	2.786	.023	.098
task x condition x view	1	20.849***	.152	< .001
task x condition x view x group	1	7.092**	.058	.009
degree x condition x view	5	3.810**	.032	.002
degree x condition x view x group	5	1.589	.014	.161
task x degree x condition x view	5	10.110***	.080	< .001
task x degree x condition x view x group	5	1.087	.009	.367
group	1	.259	.002	.612

Note. *p < .05. **p < .01. ***p < .001.

Picture Plane Rotations

For stimuli rotated in the picture plane (see Table 22), there was a main effect of task ($F_{1,116} = 4.911$, $p = .041$; $\eta_p^2 = .029$) indicating that participants were more accurate on the S/D task compared to the L/R task. The main effect of degree ($F_{5,580} = 30.479$, $p < .001$; $\eta_p^2 = .208$) suggests that stimuli positioned at 0^o were the easiest while stimuli positioned at 180^o were the most difficult. A task x stimuli interaction ($F_{1,116} = 20.806$, $p < .001$; $\eta_p^2 = .152$) shows that in both the L/R and S/D tasks, overall accuracy was greater for bodies than effectors, where greater accuracy for effectors was seen in S/D task compared to the L/R task. **For bodies**, dancers were more accurate than controls (96.5% vs. 94.8%) with comparable accuracy seen in the S/D task (95.9% vs. 94.4%) and the L/R task (97.1% vs. 95.2%). This finding was not significant likely because of a lack of power. **For effectors**, dancers were more accurate than controls (92.2% vs. 90.8%) with greater accuracy seen in the S/D task (94.6% vs. 92.6%) compared to the L/R task (89.7% vs. 89.1%). Again this is a descriptive finding and not a statistically significant one. This was further supported by a main effect of stimuli ($F_{1,116} = 67.049$, $p < .001$; $\eta_p^2 = .366$) where judgments of bodies were more accurate than judgments of effectors.

Axial Plane Rotations

For stimuli rotated in the axial plane (see Table 23), there was a main effect of task ($F_{1,116} = 10.548$, $p = .002$; $\eta_p^2 = .083$) where participants were more accurate on the S/D task compared to the L/R task. There was a main effect of degree ($F_{5,580} = 4.227$, $p = .001$; $\eta_p^2 = .035$) again indicating that stimuli positioned at 180^o were the most difficult. **For bodies**, dancers were overall more accurate than controls (92.9% vs. 91.0%).

Table 22

Analysis of Variance on Average Accuracy for Stimuli Rotated in the Picture Plane by Group

	df	*F*	η	*p*
task	1	4.911*	.041	.029
task x group	1	.120	.001	.729
stimuli	1	67.049***	.366	< .001
stimuli x group	1	.164	.001	.686
degree	5	30.479***	.208	< .001
degree x group	5	1.769	.015	.117
condition	1	18.706***	.139	< .001
condition x group	1	2.152	.018	.145
view	1	15.599***	.119	< .001
view x group	1	1.320	.011	.253
task x stimuli	1	20.806***	.152	< .001
task x stimuli x group	1	.707	.006	.402
task x degree	5	2.154	.018	.058
task x degree x group	5	.161	.001	.977
stimuli x degree	5	.998	.009	.418
stimuli x degree x group	5	.310	.003	.907
task x stimuli x degree	5	3.473**	.029	.004
task x condition	1	16.270***	.123	< .001
task x condition x group	1	1.208	.010	.274
stimuli x condition	1	87.698***	.431	< .001
stimuli x condition x group	1	2.265	.019	.135
task x stimuli x condition	1	.034	.000	.854
degree x condition	5	4.123**	.034	.001
degree x condition x group	5	1.488	.013	.192
task x degree x condition	5	4.263**	.035	.001
stimuli x degree x condition	5	.126	.001	.987
task x view	1	38.786***	.251	< .001
task x view x group	1	3.348	.028	.070
stimuli x view	1	42.981***	.270	< .001
stimuli x view x group	1	.397	.003	.530
task x stimuli x view	1	46.658***	.287	< .001
degree x view	5	4.796***	.040	< .001
degree x view x group	5	1.680	.014	.137
task x degree x view	5	1.801	.015	.111
stimuli x degree x view	5	8.709***	.070	< .001
condition x view	1	29.448***	.202	< .001
condition x view x group	1	1.002	.009	.319
task x condition x view	1	28.707***	.198	< .001
stimuli x condition x view	1	18.394***	.137	< .001
degree x condition x view	5	3.610**	.030	.003
group	1	1.733	.015	.191

Note. $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

Table 23

Analysis of Variance on Average Accuracy for Stimuli Rotated in the Axial Plane by Group

	df	*F*	η	*p*
task	1	10.548**	.083	.002
task x group	1	.172	.001	.679
stimuli	1	1.410	.012	.238
stimuli x group	1	.274	.002	.602
degree	5	4.227**	.035	.001
degree x group	5	1.136	.010	.340
condition	1	2.263	.019	.135
condition x group	1	.101	.001	.751
view	1	91.837***	.442	< .001
view x group	1	.027	.000	.869
task x stimuli	1	5.894*	.048	.017
task x stimuli x group	1	.082	.001	.776
task x degree	5	15.679***	.119	< .001
task x degree x group	5	.548	.005	.740
stimuli x degree	5	8.490***	.068	< .001
stimuli x degree x group	5	2.620*	.022	.023
task x stimuli x degree	5	7.458***	.060	< .001
task x condition	1	.773	.007	.381
task x condition x group	1	.005	.000	.942
stimuli x condition	1	26.804***	.188	< .001
stimuli x condition x group	1	1.971	.017	.163
task x stimuli x condition	1	4.056*	.034	.046
degree x condition	5	3.189**	.027	.008
degree x condition x group	5	.421	.004	.834
task x degree x condition	5	2.183	.018	.055
stimuli degree x condition	5	1.407	.012	.220
task x view	1	50.264***	.302	< .001
task x view x group	1	.428	.004	.514
stimuli x view	1	20.988***	.153	< .001
stimuli x view x group	1	.166	.001	.684
task x stimuli x view	1	15.691***	.119	< .001
degree x view	5	6.561***	.054	< .001
degree x view x group	5	.904	.008	.478
task x degree x view	5	8.990***	.072	< .001
stimuli x degree x view	5	1.300	.011	.262
condition x view	1	.205	.002	.652
condition x view x group	1	.577	.005	.449
task x condition x view	1	.418	.004	.519
stimuli x condition x view	1	13.187***	.102	< .001
degree x condition x view	5	1.718	.015	.129
group	1	2.697	.023	.103

Note. **p* < .05. ***p* < .01. ****p* < .001.

Participants had greater difficulty with left/right judgments (90.7% vs. 89.0%) compared to same/different judgments (95.1% vs. 93.0%). This is a descriptive analysis. **For effectors**, dancers overall had descriptively higher accuracy than controls (94.0% vs. 91.4%) with similar accuracy seen in the same/different task (94.9% vs. 91.8%) and the left/right task (93.1% vs. 91.0%). The comparable accuracy for bodies and effectors was reinforced by no significant effect of stimuli ($F_{1,116} = 1.410$, $p = .238$; $\eta_p^2 = .012$). There was a significant interaction of task x stimuli ($F_{1,116} = 5.894$, $p = .017$; $\eta_p^2 = .048$) where judgments of effectors were more accurate for the L/R task and comparable accuracy on bodies and effectors was seen in the S/D task.

Discussion

Dancers scored significantly higher on tests that instruct participants to engage in kinesthetic imagery. The visual imagery section of the MIQ-RS does not give explicit instructions to the participant to use a specific type of visual imagery (e.g., first person imagery or third person imagery) unlike the two visual imagery sections of the VMIQ-2. This might explain the significant difference between dancers and nondancers for visual imagery on the MIQ-RS and not on the visual imagery sections of the VMIQ-2. Additionally the MIQ-RS requires that the participant physically perform an action and then imagine performing the action without physically performing the action again. The act of physically performing the action before mentally imagining the action may influence the dancers to use visual imagery that is also inherently kinesthetic in nature.

A goal of this thesis was to evaluate expert performance on the three spatial transformations in order to assess the relationship between effector-based transformations and the transformation related to their expertise. It was hypothesized that dancers would be high in kinesthetic imagery ability and would therefore have an advantage on tasks and stimuli requiring KI (i.e., L/R tasks with bodies and body-parts). Behavioral differences on the computer-based tasks can indicate the extent to which processes are shared among the transformations or if different processes are utilized by experts. We found for L/R judgments of body stimuli rotated in the picture plane (see Table 18) that dancers are were actually *slower* across all degree disparities than controls contrary to our predictions. For body-part stimuli, again we found that dancers were overall slower in RT compared to controls. Interestingly, dancers were only slower on the L/R judgments but showed no difference on S/D judgments compared to controls.

There may be differences in how frames of reference are employed by dancers that interact with other aspects of their expertise. For example, dancers' ability to use egocentric perspective transformations may be confounded by their movement expertise (Jola & Mast, 2005; Steggemann, et al., 2011). This is a reasonable assertion given Keinänen, Hetland, and Winner's (2000) argument that dance is multifaceted, making use of many cognitive skills. Dancers use an egocentric frame of reference when performing motor movements in space. This might indicate that dancers have a greater egocentric awareness that is specific to their moving bodies in personal space reflective of their greater kinesthetic imagery. Again in dance theory, Laban (1975; Laban & Ullmann, 1966) refers to the space directly around the body within reach of the body's limbs as the Kinesphere. The Kinesphere defines zones of possible movement. A dancer's intensive experience of egocentric references frames may therefore be constrained by a dynamic instead of static understanding of space. Another possibility is that dancers' use of egocentric frames of reference is more refined relying on an intrinsic egocentric representation (i.e., body-part representations) rather than an extrinsic egocentric representation (i.e., body representation) (Creem-Regehr, et al., 2007).

Jola and Mast (2005) compared performance of dancers and nondancers on Shepard and Metzler's MRT (Shepard & Metzler, 1971) and a revised version of Zacks, et al. (2002) left/right judgment task using 2D line drawings of human bodies with one arm outstretched (MBRT; mental body rotation task). The MRT and the MBRT were used to test the two different types of references frames involved in mental imagery – object-based and body-based. Jola and Mast did not find a difference in performance between dancers and nondancers on the MBRT as they hypothesized. Our data are consistent with this finding. For bodies rotated in the picture plane, dancers were slower across all degrees of rotation compared to controls contrary to predictions that dancers would be faster because of their greater kinesthetic imagery ability (Ashton, et al., 1978). For effectors rotated in the picture plane, dancers also showed an overall slowing in RT compared to controls. Again this is not as predicted. This slowing may be due to dancers dealing with stimuli in a dynamic way by engaging in motor simulation when performing either task while controls deal with stimuli in a more static way. This explanation is further supported by a task x group interaction and a task x view x group interaction where dancers were slower on left/right judgments but no difference was seen for same/different judgments compared to controls. Comparable same/different judgments by dancers and controls are contrary to Jola and Mast's findings of a difference in performance on MRT for reaction times. They found RT was in the opposite direction where dancers were slower than nondancers. The authors postulated that this may be due to dancers applying the same strategy to solve both types of transformations. Instead of using an object-based transformation strategy, dancers could be employing an egocentric perspective transformation strategy. In fact, during debriefing some of the dancers did report using the latter strategy on the MRT. Our findings also suggest that dancers are using strategies that are possibly influenced by the other experimental tasks they had to perform. While in Jola and Mast dancers employed the perspective-based transformation strategy for both the object-based transformation task and the perspective-based transformation task, we found participants were relying on kinesthetic imagery ability, which is inherently dynamic in nature.

Steggemann, Engbert, and Weigelt (2011) studied object-based and perspective-based transformations in individuals with motor expertise for rotational movements. In their study, motor experts were gymnasts in artistic gymnastics, aero wheel gymnastics, and trampolining, as well as judoka (i.e., Judo practitioners). These groups of individuals were chosen because their expertise is not limited to one axis of rotation (as is the case, they argue, with dancers) but extends to full body rotations in all three body axes. In experiment 1, participants (controls and experts) performed a same/different task with body stimuli and with object stimuli. Motor experts showed greater response error for the transformation task with objects as compared to the transformation task with bodies, but were worse in terms of response error on both tasks compared to controls. This is contrary to our findings that dancers showed greater accuracy across all spatial transformation tasks compared to controls. Steggemann and colleagues also found that motor experts were significantly faster than controls on both same/different tasks. In our study, dancers performed similarly to controls. Performance differences on the same/different task between Steggemann, et al. and this study are possibly due to differences in motor expertise between gymnasts and dancers in relation to experience with physical body rotation. In experiment 2, Steggemann, et al. had experts and controls perform a left/right task with body stimuli. There were no significant differences between controls and experts except for an expertise x degree interaction, where experts were faster for upside down stimuli (i.e., stimuli at 180 degrees rotation in the picture plane). Again, our findings were not consistent with Steggeman and colleagues for L/R judgments in the picture plane. Although there was a significant degree x group interaction ($F_{5,580} = 2.701$, $p = .020$; $\eta_p^2 = .023$), it showed that at 180 degrees rotation in the picture plane dancers were overall slower for L/R judgments compared to controls. We also found that while controls had similar RT for the front and back views, dancers were slowest for back views of bodies contrary to previous research indicating faster RT for judgments of the backs of bodies in the normal population (Parsons, 1987a). Additionally there was no degree x group interaction ($F_{5,580} = .918$, $p = .468$; $\eta_p^2 = .008$), view x group interaction ($F_{5,580} = 2.167$, $p = .144$; $\eta_p^2 = .018$), or degree x view x group interaction ($F_{5,580} = 1.476$, $p = .196$; $\eta_p^2 = .013$) for L/R judgments of bodies rotated in the axial plane, where dancers were overall slower than controls and in particular were slower but not significantly for responses to upside down stimuli at all degrees of rotation except 0 degrees. Motor expertise appears to not be generalizable across all types of spatial transformations. Motor experts (i.e., gymnasts and Judo participants) perhaps have expertise that is more advantageous for spatial transformation tasks where stimuli are rotated in multiple axes, while dancers' expertise may be limited in a way that was not captured in our tasks. For example, a view x group interaction interestingly shows that dancers were slower to respond to the bottoms of effectors than controls but no difference was seen in RT for judgments of the tops of effectors. Despite dancers having greater experience with their effectors in varying positions based on their training, their physically experience did not equate to better performance. Dancers may have more experience than the normal population with different positions of their body parts but the majority of their experience may reinforce the typical view of effectors from above.

For bodies rotated in the axial plane, there was not a significant main effect of group or any group interactions with within-subject factors. In previous work (Study 1), SO, SV and KI were not found to predict performance on left/right judgments of bodies rotated in the axial plane. Dancers' experience with body transformations may be specific to one axis of rotation (i.e., experience with pirouettes but not flips) as evidence by longer mean RT for inverted body stimuli (M_d = 2243.734ms; M_c = 2134.565ms) and larger standard error (SE_d = 112.049; SE_c = 55.133). For body parts rotated in the axial plane, significant interactions of task x group and task x degree x group are consistent with findings for the picture plane where controls are faster for left/right judgments but slower for same/different judgments. This is further indicated by a significant task x view x group interaction where dancers are slower than controls for L/R judgments of both tops and bottoms of effectors and faster for S/D judgments of both tops and bottoms of effectors.

Given that dancers were overall more accurate than controls for all tasks and stimuli conditions and are overall slower across tasks compared to controls, it is possible that these findings are a result of a speed-accuracy trade-off. However, all participants were instructed to respond as quickly but as accurately as possible. Additionally because of the task x group interaction where dancers are slower for left/right judgments but comparable in performance to controls for same/different judgments likely this is not the case. Rather, it may be a result of dancers using different processes such as kinesthetic imagery as opposed to spatial orientation ability or spatial visualization ability. Further study will have to be done to extend these findings to other tasks and stimuli.

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SIGNIFICANCE AND CONTRIBUTIONS

Anecdotally, we know from experience that people differ in their spatial abilities as illustrated in varying aptitude to read a map, solve geometry problems, or dance. Even among spatial experts, such as gymnasts and surgeons, we observe differences in spatial ability inherent in their talent and professional training. Individual differences are further pronounced in well documented gender and cultural differences in spatial ability (e.g., Haun, Rapold, Janzen, & Levinson, 2011; Linn & Peterson, 1985; McGee, 1979a). Previous research supports the idea that spatial ability is made up of associated factors, but there is little agreement on how those factors are characterized, what constitutes a factor, or how many distinct factors exists (e.g., Carroll, 1983; Hegarty & Waller, 2005; Lohman, 1979). This is largely because the psychometric tests that have traditionally been used to measure spatial ability were not motivated by theories of spatial thinking or by a definition of spatial ability (Hegarty, 2010; Uttal, et al., 2012). In contrast to this bottom-up approach, I argue that the nature of spatial ability may be better explained by taking a top-down approach which investigates the relationship of spatial ability to higher level spatial thinking and to spatial expertise. This approach redefines the boundaries of spatial ability research by integrating disparate literatures in expertise, linguistics, neuroscience, and cognitive psychology thereby allowing for new techniques and methodologies to be applied to spatial cognition research. As evidenced in this thesis, the role of kinesthetic imagery ability in spatial transformations broadens our understanding of these processes. The spatial expertise of dancers is further specified as a function of kinesthetic imagery ability and use of spatial transformations given changing task parameters.

Spatial thinking is multifaceted involving the interrelated abilities of understanding space, representation, and reasoning. It is central to everyday decision making, communication, and navigation and is critical to success in the STEM (i.e., science, technology, engineering and mathematics) disciplines (Newcombe & Shipley, in press; Wai, Lubinski, & Benbow, 2009). Entry and retention in the STEM disciplines is affected by our spatial thinking ability, which disproportionately limits the accessibility of these fields to minorities and women (Geary, Saults, Liu, & Hoard, 2000; Newcombe, 2010).

Spatial thinking has been under-appreciated, under-researched and under-theorized. In a recent report from the National Research Council (NRC; Downs & DeSouza, 2006), it was recommended that K-12 curriculums integrate spatial thinking in all courses. However, a lack of research supporting the claim that improved spatial skill can transfer has led the NRC to challenge researchers to undertake investigations that focus on improving spatial thinking in a generalizable way. This highlights the importance of understanding how spatial thinking can be improved through structured practice and direct experience (Ericsson, et al., 1993; Sloboda, et al., 1996). A few papers lend support to the idea that general spatial thinking can be trained (Baenninger & Newcombe, 1989; Feng, Spence, & Pratt, 2007; Green & Bavelier, 2003; Terlecki, Newcombe, & Little, 2008; Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008). One approach to determining teaching and training interventions is to identify spatial experts who excel in desirable abilities or component processes and use their training as a model. Chi (2006) referred to this approach as the relative approach, where expertise is considered to be a level of proficiency that is achievable by novices. More broadly, examining individual differences in spatial abilities (both in the normal population and in expert populations) is important for understanding and facilitating spatial thinking, which is present in all disciplines.

The study of spatial experts is an inherently interdisciplinary approach that leads to unexpected insights. Specifically I take an interdisciplinarity approach as defined by Klein (1990). According to Klein, interdisciplinarity refers to the joint application of methods and knowledge of different disciplines to shared questions where each discipline gains greater knowledge than from working alone. This is a novel perspective in the spatial thinking literature and one that has implications across disciplines.

CONCLUSIONS AND FUTURE DIRECTIONS

The goal of this thesis was to understand how different spatial transformations may recruit different processes and how this may be influenced by spatial ability and/or spatial expertise. One experiment was analyzed in multiple ways to address two aims. The first aim was to determine whether effector-based transformations require spatial orientation ability, spatial visualization ability, or kinesthetic imagery. The processes involved in effector-based transformations are unclear based on the existing literature. Given that behavioral and neuroimaging data support a dissociation between object-based and perspective-based transformations (e.g., Hegarty & Waller, 2004; Zacks, Hazeltine, et al., 1999; Zacks & Michelon, 2005; Zacks, Rypma, et al., 1999) this previous work can be used as the basis to understand effector-based transformations. By testing all three spatial transformations in the same study and evaluating both spatial ability and spatial expertise, comparisons could be made with the existing literature to uncover shared or distinct mechanisms involved in effector-based transformations. This paradigm also allowed for the testing of established relationships between transformations and spatial ability further expanding on the current literature.

The second aim was to explore the role of spatial expertise in the processing of spatial transformations. Spatial experts trained in a specific spatial transformation, such as spatial awareness in dance, were predicted to excel on the specific type of transformation related to their expertise – effector-based transformations for dancers. The overall reaction time profiles of spatial experts on spatial transformation tasks were predicted to show the degree to which the three transformations share processes. Dancers and nondancer controls were compared on psychometric tests of three spatial ability factors and confirmed that dancers do significantly differ from controls in kinesthetic imagery ability. Behavioral differences on computer-based reaction time spatial transformation tasks were also evaluated as a function of expertise group. While it was predicted that dancers would have an advantage on tasks and stimuli requiring kinesthetic imagery based on their high kinesthetic imagery ability, I found that dancers were actually slower on these tasks. This suggests that spatial experts are not simply at either extreme of performance but rather they likely utilize different processes to solve these transformation problems. Dancers, in this case, may process stimuli in a dynamic way as opposed to processing stimuli in a static way as been previously shown in the normal population.

The results provide evidence that spatial ability underlies spatial transformations in a more complicated way than previously thought. Further investigation is necessary to generalize these results to other axes of rotation and additional tasks that involve spatial transformations. The finding that kinesthetic imagery influences L/R responses in the picture plane may be attributed to both the measures of kinesthetic imagery used as well as the task parameters (e.g., the stimuli and task demands).

Expert performance in Study 2 suggests that dancers are not consistent with normal performance on spatial transformations (Study 1). That is, they are not simply performing better or worse than controls. Rather it appears that experts are using different processes to perform the spatial transformation tasks. While these behavioral measures indicate a difference in performance between novice and expert groups, additional measures are needed to determine if dancers are in fact using a dynamic strategy. Neuroimaging would be one way to further explore spatial expertise and spatial transformations.

This experiment design could be used to behaviorally identify other relationships between spatial ability factors and spatial processes. These relationships could also then be clarified using brain imaging. Differences could be evaluated behaviorally through traditional psychometric tests, computer-based spatial ability tests and perception-action measures and neurally through functional MRI. Second, spatial expertise as a construct could be more explicitly defined by behavior and performance outcome (Ericsson & Lehmann, 1996; Lee, Steyvers, de Young, & Miller, 2011; Shanteau, Weiss, Thomas, & Pounds, 2002; Weiss & Shanteau, 2003). By identifying differences in spatial ability as they relate to spatial processes, tasks could be considered relative to individual differences in spatial ability across the normal population, which could lead to training interventions for those low in key spatial ability factors, and relative to differential processing in experts, which could be more advantageous given the task demands. The utility of finding individual differences may be important in developing non-traditional training interventions, such as dance movement or architectural drafting exercises, as well as informing theory about spatial thinking.

A more focused way of understanding the relationship of spatial ability factors and spatial thinking processes is to use a theory-driven framework. Newcombe and Shipley (in press) suggest a typology that takes a theory-driven approach to understanding spatial thinking. Stemming from a multidisciplinary perspective, they propose a classification system for spatial representations that distinguishes information as intrinsic or extrinsic given a static or dynamic task. Intrinsic information defines the object such as its features and the relationship of those features. Extrinsic information defines the relationship among objects, between objects, and within reference frames. Spatial skills can then be defined within four categories: intrinsic-static, intrinsic-dynamic, extrinsic-static and extrinsic-dynamic.

Both intrinsic and extrinsic skills are crucial to understanding spatial concepts and spatial representations – a key spatial capability identified by the NRC. Extrinsic-static skills include the ability to understand abstract spatial principles such as the relationship of locations on maps and may be related to the spatial abilities of *spatial perception*, which is the ability to determine spatial relationships in midst of distracting information (Linn & Peterson, 1985), and *spatial scanning*, which is speeded exploration of a large or complex spatial field (Ekstrom, et al., 1976). Extrinsic-dynamic skills include the ability to visualize the environment from another perspective and may be related to the spatial ability of *spatial orientation*, which is the ability to mentally transform one's perspective relative to spatial forms, or to the spatial ability of *kinesthetic imagery* as is suggested in this thesis. Overall the existing behavioral literature (e.g., D'Oliveira, 2004; Hunt, Pellegrino, Frick, Farr, & Alderton, 1988) indicates that dynamic and static spatial skills are separable abilities. While some of the behavioral research is contradictory, the distinction between dynamic and static spatial skills has been further clarified by neuroimaging research (e.g., Lamm, Windischberger, Leodolter, Moser, & Bauer, 2001; Zacks, Ollinger, et al., 2002), which shows differences in activation of motor areas of the brain. Additional studies (e.g., Law, Pellegrino, & Hunt, 1993) suggest that there are robust individual differences in dynamic spatial ability that are partially mediated by experience.

There are also well documented individual differences in static spatial ability (e.g., McGee, 1979b; Zacks, Mires, et al., 2002) that can be eliminated through training. Intrinsic-static skills refer to the ability to perceive objects or spatial configurations among noise and may be related to the spatial ability of *object visualization*, which is the ability to process information about the visual properties of objects. Intrinsic-dynamic skills refer to the ability to visualize and mentally transform objects and may be related to traditional measures of *spatial visualization*, which is the ability to mentally transform objects. Previous studies (e.g., Kozbelt, 2001; Kozhevnikov, et al., 2005) have investigated object visualization in visual artists and spatial visualization in scientists. Findings indicate that visual artists are more likely to utilize intrinsic-static skills while scientists are more likely utilize intrinsic-dynamic skills. Additionally, specific spatial ability in spatial visualization is positively related to successful mathematical problem solving (Hegarty & Kozhevnikov, 1999).

I suggest that individual differences in spatial ability may be more pronounced in architects, modern dancers, visual artists and scientists due to their extensive professional training and experience. Architects deal with spatial concepts at varying architectural scales (Ferguson, 2001). As a result, the medium for architects is mainly representational, taking the form of technical drawings, physical and computer models, and mock-ups (Cahtarevi, 2008). These architectural representations involve extrinsic-static information. According to modern dance theory (Laban, 1950), a fundamental concept is spatial awareness of the dancer’s body in relationship to the environment in terms of the

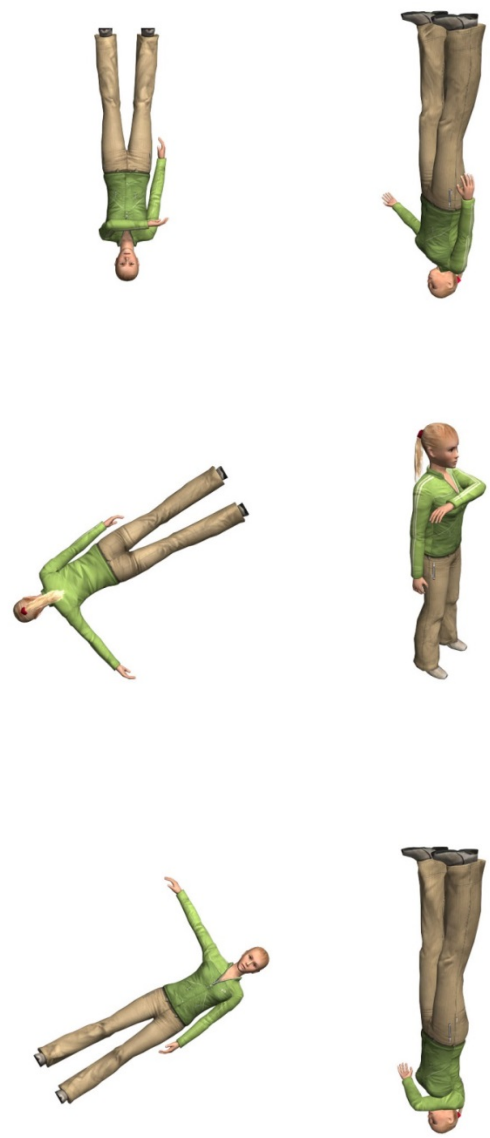
Kinesphere and Dimensional Cross (i.e., the orientation of the body in space with respect to three axes – vertical, horizontal, and sagittal). This spatial awareness is considered relative to movement and is largely body-based supporting the argument that dancers deal with extrinsic-dynamic information (Leman & Naveda, 2010). The expertise literature would advocate that visual artists have specialized knowledge of pictorial conventions based on the assumption that artists are better at drawing than the normal population. Kozbelt (2001) suggested that that artists are good at understanding and analyzing the visual structure of the world which in turn contributes to good drawing. This skill would be intrinsic-static in nature. Scientists such as chemists and physicists show superior performance on spatial visualization tasks based on their experience with both dynamic and static visualization of schematic images (Kozhevnikov, et al., 2010; Kozhevnikov, et al., 2007). The distinction between architects as more extrinsic-static, modern dancers as more extrinsic-dynamic, artists as more intrinsic-static, and scientists as more intrinsic-dynamic would offer a model for novel training interventions and provide further evidence of a disassociation between intrinsic/extrinsic and static/dynamic skills as well as potentially support the existence of discreet spatial ability factors.

Another research direction is to study the use of mental imagery in dance. Dancers are highly skilled movement experts (Allard & Starkes, 1991) that employ mental imagery in order to acquire and improve dance skills, choreography, and self-confidence (Fish, Hall, & Cumming, 2004; Hanrahan & Vergeer, 2000; Taylor & Taylor, 1995). Fish, Hall, and Cumming (2004) proposed an applied dance imagery model (adapted from Martin, Moritz, & Hall, 1999) that accounted for five different uses of imagery – cognitive general, cognitive specific, motivational general-mastery, motivational general-arousal, and motivational specific. Fish, et al. found that elite ballet dancers do utilize imagery for both cognitive and motivational functions. Further study of imagery use in dancers has implications to understanding the acquisition of skilled movement. A comparison of ballet dancers and modern dancers may reveal differences in mental imagery as a function of differences in movement training.

Another direction is the study of action simulation in dancers. Research has proposed that there is a similar pattern of neural activity for performing, observing, and imagining the same action (Rizzolatti & Craighero, 2004; Rizzolatti, Fogassi, & Gallese, 2001). Action simulation has also been shown in functional magnetic resonance imaging (fMRI) studies of dancers (Calvo-Merino, et al., 2005; Cross, Hamilton, & Grafton, 2006). Interestingly, Cross, Hamilton, and Grafton (2006) were able to show activation of action simulation and action observation brain regions after learning and rehearsing novel whole body dance sequences during a 5-week period. In this study, professional modern dancers learned dance sequences where half of the sequences were physically rehearsed and the other half of sequences were unpracticed. Participants were scanned each week to track the potential development of a motor simulation as an outcome of 5 hours of rehearsal each week. The authors also found that activation of the action simulation system was modulated by the dancers' self-ratings of their ability to perform the observed movements and of their motor experience. These findings have implications to the study of imagined actions and may clarify findings from this thesis.

APPENDIX A

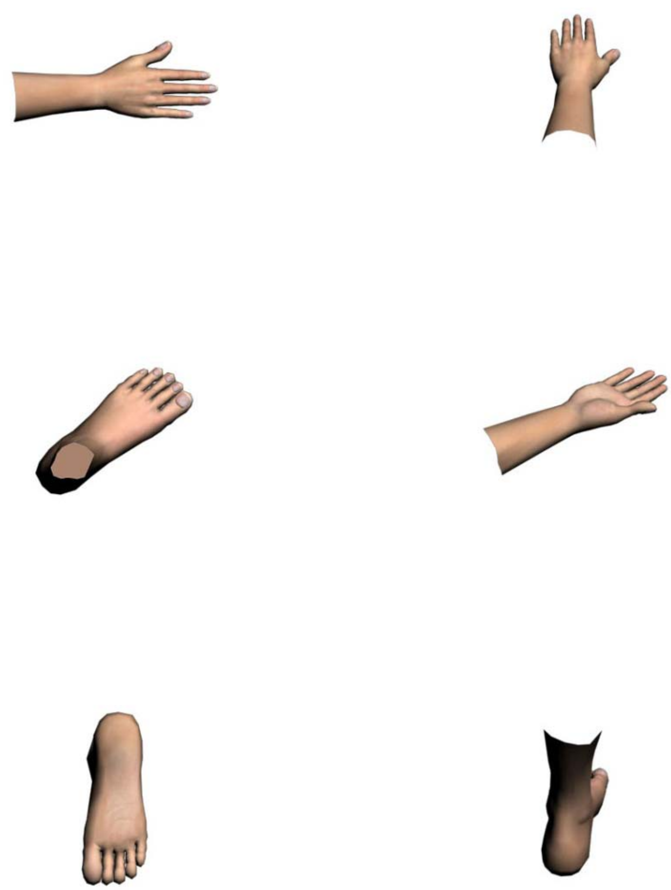
BODY STIMULI



Additional examples of body stimuli by condition and view rotated in the picture plane (*left*) and in the axial plane (*right*)

APPENDIX B

EFFECTOR STIMULI



Additional examples of effector stimuli by condition and view rotated in the picture plane (*left*) and in the axial plane (*right*)

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